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Using inbenthic species to assess the ecological status of restored salt marshes

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USING INBENTHIC SPECIES TO ASSESS THE ECOLOGICAL STATUS OF RESTORED SALT MARSHES

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ABSTRACT

USING INBENTHIC SPECIES TO ASSESS THE ECOLOGICAL STATUS OF RESTORED SALT MARSHES

By Rena A. Obernolte

Habitat parameters and inbenthic macroinvertebrate community structure were examined in four sets of paired salt marshes San Francisco Bay to compare the ecological functioning of restored (10-20 years old) to natural tidal salt marshes. Canonical correlation of habitat parameters to species abundance showed that *Macoma* spp., *Neanthes* spp. and *Heteromastus* spp., preferred low redox habitats with low percent plant cover, whereas polychaete A preferred high redox and plant cover. Oligochaetes preferred low redox, low salt, more basic pH, low temperature, low volume organic matter, and low percent plant cover. Reference habitats tended to have a higher volume of organic matter, higher redox potential, higher percent vegetation cover, lower percent oligochaete composition and higher percent polychaete composition. Species evenness was highly correlated to volume organic matter ($r = 0.82$) but negatively correlated to oligochaete abundance ($r = -0.70$). Percent polychaete abundance was negatively correlated to oligochaete abundance ($r = -0.90$). Reference marshes tended to have a higher percent composition of polychaetes (67%) than restored marshes (43%). These findings provide potential restoration parameter values for south SF Bay restoration projects.

Key words: salt marsh; restoration; redox; organic matter; invertebrate; Polychaeta; Oligochaeta; Bivalvia; San Francisco Bay.

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INTRODUCTION

San Francisco Bay salt marshes are very important to many endangered and threatened species that are specifically adapted to this harsh environment. Natural or human induced stresses have led to the loss and degradation of over 90% of the Bays' marshlands (Josselyn et al. 1991). Losses continue today as a result of development and human activities. If marshes cannot be protected, developers are required by the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA) to mitigate impacts to wetlands. A typical mitigation is to restore degraded wetlands into functional wetlands.

However, relatively little is known on how to fully restore a functional wetland (Zedler 1996). A primary problem is that there is insufficient knowledge on how marsh ecosystems function. Hobbs and Norton (1996) note that a major problem in restoration is the lack of data on natural systems that provide reference data for restoration goals. This lack of knowledge hinders the development of ecological goals that can be used to determine the relative ecological status of restored marshes. In order to develop ecological goals, basic community structure and habitat preferences of the marsh fauna must be known.

To date, there have been relatively few studies on the San Francisco Bay salt marshes. Nichols and Pamatmat (1988) have extensively studied the Bay's inbenthic community for decades. Their studies describe the spatial and temporal distribution of the invertebrates living in the Bay and on the mudflats, but do not focus on the marshes. Little is known on the Bay's inbenthic invertebrate community structure or their habitat preference. Habitat preference must be inferred from studies done elsewhere. This research was undertaken to add to the information on inbenthic invertebrate community structure and their required habitats in San Francisco Bay salt marshes. Studies have affirmed the need for research on the organisms in the lower trophic levels of the food chain in salt marshes (Josselyn, Zedler, and Griswold 1990; PERL 1990). Another purpose of this research is to provide data on the progress of salt marsh restoration projects occurring in the south San Francisco Bay Area.

Sample collection for this study was done in June 1998, after an exceptionally high rainfall year that was the result of an El Niño event. This thesis quantified eight of the most dominant benthic invertebrate species at four restored salt marshes and at four paired adjacent reference marshes. It also examined several environmental properties such as temperature, salinity, pH, redox depth, dissolved oxygen content, volume of organic matter and percent plant cover in relation to species diversity, abundance and distribution.

This study yields new data on the inbenthic community in the southern portion of the San Francisco Bay. The goal of the thesis is to assess the relationship between inbenthic macroinvertebrate species and several relevant environmental properties. First, this research identifies some components of the habitats required for individual infaunal species found in the salt marsh tidal channel environment. Secondly, it describes community structure similarity between the marshes studied. Next, it describes habitat attribute similarities between the study sites. Additionally, this thesis determines how closely restored marshes resemble their reference sites with respect to the benthic community structure and their channel habitats. This thesis also correlates percent species abundance, diversity, and volume organic matter. Finally, it provides baseline data on the inbenthic community for the eight marshes examined. This study found that restored marshes lack inbenthic community diversity and large amounts of soil organic matter, even 10 years post restoration, although species abundance was higher in restored marshes.

BACKGROUND

Importance of Salt Marshes

Salt marshes are very important habitats for both humans and wildlife. Wetlands areas are recognized as one of the most productive ecosystems in the world (Knox 1990). They are extremely dynamic habitats, and are exceedingly important to many endangered and threatened species that have specifically adapted to this harsh environment. This habitat provides food and cover for many species of wildlife, both permanent residents and migratory visitors (Zedler 1996). Marshes provide benefits for humans in the form of flood control, erosion protection and ground water recharge. They improve water quality by removing nutrients, trapping sediments, heavy metals and toxic organics from urban run-off (Coats and Williams 1990).

Perhaps the greatest value of San Francisco Bay salt marshes lies in the habitat they provide for the many endemic and endangered species (Josselyn 1983). Unfortunately, the San Francisco Bay marshlands have suffered considerable degradation and habitat loss. Salt marsh ecosystems remaining in the San Francisco Bay cannot achieve optimum levels of production. This loss or degradation of habitat, which leads to habitat fragmentation, has led to the decline of many salt marsh endemic species such as the salt marsh harvest mouse (*Reithrodontomys raviventris*), and the clapper rail (*Rallus longirostris*) (Josselyn, Zedler and Griswold 1990).

Threats to San Francisco Bay Area Salt Marshes

A few of the major threats to the salt marsh ecosystem are agriculture, salt mining and urban growth. Beginning in the late 1930s through the 1940s, most marshes around the San Francisco Bay were diked for flood control or filled for development. Land tilled for agriculture oxygenates the organic matter in former estuarine sediments. Soil compaction occurs as a result of this aerobic decomposition of organic matter in the soils and from the de-watering of sediments. The salt mining industry covered marsh habitat with salt evaporation ponds which has resulted in significant habitat loss and also causes soil compaction. Soil compaction leads to subsidence which decreases elevation. Marsh habitats are directly influenced by elevation. Small changes in elevation can dramatically alter habitats in marshlands by altering tidal inundation times (Josselyn 1983). Fortunately, these threats are at least partially reversible.

Urban growth on the other hand is effectively permanent. Once a salt marsh has been built upon, it is very difficult to reclaim (Curry et al. 1985). Ground preparation for buildings increases erosion and sediment input into streams, and the disposal of domestic and commercial waste decreases water quality. Agriculture and flood control, which required the diking of wetlands in the past, have severely restricted tidal flow.

Another threat to the Bay's marshes is the invasion by exotic species. Exotics species account for more the 80% of the infaunal biomass in the south San Francisco Bay. They primarily enter the bay via foreign ballast water discharged from cargo ships. Exotic species have also been inadvertently introduced from the bait used by sports fishermen. Additionally, exotics have been intentionally introduced by oyster industry practices (Carlton 1975; Nichols and Pamatmat 1988). Introduced organisms are known to displace the natural fauna which can alter the ecosystem by upsetting natural predator-prey relationships, community structure, and ecological interactions (Grosholz and Ruiz 1995).

The introduction of the Asian clam, *Potamocorbula amurensis*, has led to the decline of the copepod population, altering community structure and shifting predator-prey relationships (Kimmerer, Gartside, and Orsi 1994). The introduced green crab, *Carcinus maenas*, has lead to a decline of some bivalve populations. This decline in the bivalve populations has been correlated to the decline in the number of shorebirds in Bodega Harbor (Grosholz and Ruiz 1995). *Carcinus maenas* competes with native crabs such as *Hemigrapsus oregonensis*, *H. nudus* and *Pachygrapsus crassipes* and has the potential to displace them (Cohen, Carlton, and Fountain 1995). Although the effects of this exotic invasion are not fully known, native species are often displaced. All of these common threats to the marsh must be managed to maintain functioning ecosystems.

Regulatory Issues

Still the greatest threat to marsh habitats is the loss from development. Mitigation practices arose as a result of federal agencies responsibility to ensure a "no net loss" policy for wetlands (Zedler 1992). The National Environmental Policy Act (NEPA) of 1969 was the first federal act that required federal agencies to examine the environmental consequences of their actions. To do this, an Environmental Impact Statement (EIS) is prepared for all major federal actions and reviewed before the action is allowed. Executive Order number 11990 of NEPA specifically addresses the protection of wetlands on federal property or to avoid "long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands wherever there is a practicable alternative" (NEPA 1969). In California, there is a parallel to NEPA, the California Environmental Quality Act (CEQA). CEQA requires an Environmental Impact Report (EIR) to address significant impacts of projects and provide mitigations and alternatives to reduce those impacts.

To avoid hindering development, mitigation has, in some cases, allowed the destruction of wetlands with the agreement to restore or create others. The major permitting agency with jurisdiction over wetlands is the U.S. Army Corps of Engineers (USACE). Their authority is derived from Section 404 of the Clean Water Act which requires that they regulate dredge or fill in waters of the U.S. In the San Francisco Bay Area, the San Francisco Bay Conservation and Development Commission (BCDC) is the regulatory agency that controls development in the Bay's wetlands. BCDC gets its authority from the McAteer-Petris Act under which they regulate dredge or fill of the San Francisco Bay. The California Coastal Commission, which gets its authority under the Coastal Act, gives wetlands a high priority for conservation and enhancement. Under the Commission's guidelines, there should be *no net loss* of wetlands, and "mitigation measures should restore areas which are no longer functioning in a manner beneficial to wetland species" (CCC 1975)

The federal and state Endangered Species Acts not only provide protection for endangered species, but also for the protection, and if necessary the enhancement, of the endangered species habitat. U.S. Fish and Wildlife Service and the California Department of Fish and Game are the federal and state agencies, respectively, that administer the endangered species acts. Restorations are undertaken as mitigation for dredge or fill or more appropriately to restore species' habitats. Restoration is mandated by U.S. Fish and Wildlife Service (FWS) in recovery plans to rehabilitate habitat for endangered species (Zedler 1995). Many restorations are undertaken by resource agencies to improve stocks of selected species or enhance biodiversity in general (Zedler 1996).

Many San Francisco Bay wetlands are being restored by government and non-profit agencies. Others have been restored by volunteer efforts. Abandoned salt evaporation ponds are prime locations for tidal marsh restorations in the San Francisco Bay Area. These ponds originally destroyed most of the SF Bay wetlands and their restoration is necessary to restore the full functioning of the SF Bay (Goals Report 1999). Strict development regulations have resulted in these ponds being sold to agencies for restoration instead of being developed (Kruczynski 1990; Sverdrup & Parcel and Associates 1985).

In spite of the fact that several salt marshes around the San Francisco Bay have recently been the subject of restoration (Josselyn 1983; Sverdrup & Parcel and Associates 1985; Josselyn, Zedler, and Griswold 1990; Johnson, Hu, and Krone 1994), there is no evidence to indicate that restoration projects are accomplishing what they are intended to do. A lack of monitoring data and specific ecological goals are the primary reasons restorations cannot be evaluated (Josselyn 1983). Studies of wetland mitigations show that few are in compliance with the regulations, so often partial or complete project failures occur (Race 1985). Additionally, many restored marshes do not fulfill ecosystem functions, so wetland losses continue (Kusler and Kentula 1990).

Creating specific and verifiable ecological goals in wetland restoration has historically been a weakness in marsh restorations (Josselyn 1983). Ecological goals are often not well defined. Part of the reason for this weakness is that salt marsh ecosystems are very dynamic caus: .g difficulty in setting specific goals. In order to make recommendations, data on the variation in basic community structure and species inter-relationships are needed. Species interactions, habitat requirements and community structure of salt marshes are just beginning to be understood (Zedler 1995).

<u>Marsh Restoration Model Sites</u>

A typical way to determine restoration goals of habitat equivalency is to compare a restored or constructed habitat to a natural one. The natural habitat is called a "model site" or "reference site", and is usually relatively undisturbed by human actions. Model sites are studied intensively to determine the species structure and ecosystem processes upon which the species depend, in order to provide ecological goals for a restored site. Unfortunately, there are few habitats unaffected by humans to serve as perfect model sites, so in this case, the least disturbed system in an area serves as the model site (Shisler 1990; Aronson, Dhillion, and Le Floc'h 1995). It is critical that more than one reference site be examined due to natural variations between sites. Reference sites should be the most undisturbed ecosystem available of a similar habitat type located in close proximity to the restoration site. Typical parameters measured at reference sites to set restoration targets are hydrology, vegetative cover, fauna structure, biomass, and diversity, soil and water quality factors such as salinity, pH, temperature, and nutrient levels (PERL 1990).

Studies on Salt Marsh Benthic Communities

Although there are many studies that examine the spatial and temporal distribution of benthic organisms in *Spartina* marshes, these studies are predominately located in the East or Gulf coasts of the U.S. (Cammen 1976; Kneib 1984, Minello and Zimmerman 1992), and/or in Southern California *Spartina* (cordgrass) marshes (Zedler 1986, 1987; Zedler and Langis 1991; Levin, Talley, and Thayer 1996; Levin, Talley, and Hewitt 1998). Levin, Talley, and Hewitt (1998) caution against comparing California marshes to East coast marshes. Major differences were found in studies comparing the marshes in the two locales with respect to the benthic communities. Macrofaunal densities in Pacific coast marshes were found to be 3 to 10 times higher, and contained fewer polychaetes and a greater percentage of oligochaetes (especially Enchytraeidae) than the Atlantic marshes.

Spatial distribution of the more conspicuous invertebrates in intertidal marshes, such as the crabs and snails, is well known but little is known about the abundant, small, inconspicuous infaunal organisms of salt marshes such as the polychaetes, oligochaetes and bivalves. In particular, little is known about the inbenthic organisms living in San Francisco Bay *Salicornia* marshes. Unfortunately, published studies that focus specifically on the benthic community in San Francisco *Salicornia* marshes are rare. Most of the studies done on the SF Bay salt marshes focus on plant cover, hydrology, or soil characteristics (Josselyn 1983; Josselyn, Zedler, and Griswold 1990; Coats and Williams 1990; St. Omer 1994), but the more inaccessible attributes, such as the inbenthic macrofauna, are rarely addressed. Any knowledge regarding benthics in the Bay salt marshes must be implied from studies done in other locations.

Soft-Substrate Invertebrate Distribution

Studies on epibenthic organisms are fairly well represented in the literature. In particular, one snail species, *Melampus bidentatus*, has been studied in detail. Its tolerance ranges for salinity, temperature and desiccation have been well documented, as well as its predator-prey relationships (Kneib 1984). This is not true for most of the infaunal organisms living in the salt marshes; only some general patterns of distribution have been described for the infaunal organisms.

Infaunal organisms inhabit both subtidal and intertidal estuarine habitats, but most of the parameters that affect their distributions are largely unknown (Kneib 1984). Descriptions of the distribution patterns of organisms living in soft-substrates are imperative to our understanding of community dynamics, but are inadequate in the literature. Many unresolved questions concerning the spatial and temporal patterns of invertebrate distribution and abundance in salt marshes challenge our understanding of soft-substrate community dynamics.

Kneib (1984) divides the factors that influence inbenthic distribution patterns into 4 categories: (1) density-dependent processes (e.g., adult-larvae interaction, interspecific competition), (2) selective larval settlement or mortality, (3) physical factors expressed through habitat preference, and (4) unpredictability of cyclic physical disturbances.

This thesis addresses the third set of community dynamic influences by correlating the physical substratum properties to the abundance and diversity of species. Sanders (1958, 1960) demonstrated that benthics do exhibit preferences for specific environmental niches. Researchers have suggested that the level of sediment organic carbon is the largest determinant to marsh productivity and invertebrate assemblages (Cammen 1976; Havens, Varnell, and Bradshaw 1995; Minello and Zimmerman 1992). Vegetative cover is also thought to influence distribution in the soft bottom community, restricting some species, while providing essential habitat for others. These parameters will be measured in this thesis research as well as other parameters such as salinity, pH, temperature, dissolved oxygen, and redox depth potential (RPD). Kneib (1984) believes that temperature and salinity do not restrict the distribution of benthic organisms because they are exposed to a wide range of these parameters. This hypothesis was tested in the canonical correlation shown later in this study. Other important environmental parameters such as soil particle size, pollution or heavy metal concentrations, and water turbidity were not included in this thesis due to resource limitations.

Restored vs. Natural Marshes

There are several studies comparing benthic organisms in a natural marsh system to constructed marshes. Most of these are studies were completed in East or Gulf coast marshes (Cammen 1976; Zedler and Langis 1991; Minello and Zimmerman 1992; Levin, Talley and Thayer 1996). Results of these studies show significant differences in benthic species composition and abundance between newly formed marshes that are 2 - 5 years old, and relatively undisturbed systems. Generally, newer marshes had a lower density of organisms than older marshes. It is thought that newer marshes have not yet developed the functional equivalency of older marshes, especially for food production. Older marshes tended to have a higher polychaete composition, while insect larvae dominated the constructed marshes. Some studies (Sacco, Booker, and Seneca 1988; Fell et al. 1991; Peck et al. 1994) conclude that restored marshes begin to resemble natural marshes in species composition after 13-15 years, although species abundance is often higher in restored marshes.

This thesis focuses on the inbenthic community living in the tidal channels of several salt marshes in the South San Francisco Bay. This study was limited to tidal channels because pilot surveys and published studies suggested that polychaete density and diversity is higher in the channels than in the high marsh areas (Minello, Zimmerman, and Medina 1994; Levin, Talley, and Hewitt 1998). This thesis addresses species-habitat preferences as well as provides insight into how some restored marshes compare to natural systems in relation to the benthic community and habitat structure.

RESEARCH QUESTIONS

This thesis is a step toward establishing ecological criteria for inbenthic macroinvertebrates in restored salt marshes in the San Francisco Bay Area. Basic information regarding a late spring/early summer season of soft bottom invertebrate communities will be obtained. Species abundance was correlated with physical habitat data using the canonical correlation technique. The environmental parameters measured were redox potential depth (RPD), pH, salinity, temperature, percent plant cover and volume of organic debris. This thesis also examined similarities of community structure and habitat similarities between the marshes studied using the multidimensional scaling ordination. Patterns between restored and reference sites with respect to their environmental parameters were investigated using the multivariate principle components analysis (PCA). Correlations between species abundance and/or environmental parameters were also determined using the Pearson Product Moment Correlation Coefficient technique.

The reference sites served as the standards for assessing the ecological status of the restored marshes. They were chosen because they are some of the most naturally functioning marshes left in the Bay. Understanding ecological parameters at model sites allows ecologists to set clearly defined goals for restoration projects as well as to determine which parameters are the best predictors of the success of restoration projects.

This study of four restored and four relatively undisturbed San Francisco Bay wetlands addressed the following research questions: 1) Is there a relationship between substratum physical characteristics and the abundance and distribution of the benthic community? 2) How similar are inbenthic macroinvertebrate species diversity and abundance between sites, or between restored and reference sites? 3) How similar are the habitat characteristics between sites, or between restored and reference sites?

To address these questions, core samples were taken in June 1998. The best time to measure inbenthic invertebrate communities is in the late spring, or early summer which is considered the peak recruitment time for these species (Sardá, Foreman, and Valiela 1995; Levin, Talley, and Thayer 1996). Comparable sets of core samples from reference and restored marshes were collected from four study sites: Don Edwards San Francisco Bay National Wildlife Refuge in Fremont, California; Hayward Area Recreation Department (HARD) in Hayward, California; Bair Island in Redwood City, California; and Shoreline Regional Park, in Mountain View, California. Core sampling methods used were similar to those used by Kalejta and Hockey (1991) and Pittman (1996). Samples were washed and sieved through 0.5 mm sieve to collect macroinvertebrates. The size cut-off for macroinvertebrates is 0.5-1.0 mm, but for macroinvertebrate population studies, the 0.5 mm cut-off is recommended in order to sample the entire population (Nichols and Pamatmat 1988). The resultant debris and animals collected from the sieving process were preserved in 70% isopropyl alcohol with Rose Bengal stain. Dominant organisms were identified and counted for correlation studies and structural similarity studies.

Benefits of This Study

Analyzing the distribution and abundance of the benthic organisms and relevant habitat parameters in tidal salt marshes provides a greater understanding of the basic ecology of these critical areas. Correlating species diversity and abundance to environment factors provides information on species habitat requirements and information on species-environment interactions. This study can be used as a building block to further studies in the SF Bay marsh habitat. This study will inform restorationists and managers about the relative state of four restored marshes in comparison to four, geographically connected, relatively undisturbed marshes. Within California, there are many wetland restoration sites where this research could be applied. This work will benefit the Army Corps of Engineers, US Fish and Wildlife Service, California Environmental Protection Agency, the Department of Fish and Game, SF Bay Conservation and Development Commission and consultants who design and implement wetland restoration enhancement plans and monitoring strategies.

Ultimately, this study can aid in the development of ecological goals that can be used to evaluate the extent to which restoration sites are achieving ecological functioning. These goals can be used in management plans to ensure successful marsh restoration that will preserve the endangered species inhabiting these areas. It will provide a gauge with which to judge the relative success of marsh restoration.

Studv Limitations

Limitations of this study are the following. Samples were only collected for one spring season, reflecting whatever climatic disparities occurred within the year. The year this study commenced was after two exceptionally high rainfall years brought on by an El Niño event. The similarity analysis of invertebrate species between sites, as well as the habitat comparisons between natural and restored sites is a pattern recognition technique, not a hypothesis test. This analysis will determine patterns between the two types of habitats with respect to the invertebrate communities or habitats. This information will provide the basis for further research and hypothesis testing on salt marsh ecology. Although this study can only be a snapshot of the marshes in one particular season, this research will be useful in providing insight into community dynamics of the benthic invertebrate community. This will be especially true when used in conjunction with other studies previously completed on these marshes on plant cover and soil characteristics (Trulio unpublished data). This study is also provides recommendations on some useful parameters to measure in marsh restoration monitoring programs.

Benthic invertebrates are only one way of monitoring habitats to determine success of restoration projects. Other parameters usually measured such as vegetative cover and canopy structure, are also important for evaluating habitat and have been studied elsewhere (Zedler, 1996). This thesis can not cover all major variants within salt marsh systems. Only four restored marshes and four reference sites were examined. The restored sites were between the ages of 10 - 20 years of age, and are fully tidal, not culverted. The field sampling of this study was limited to the marsh tidal channels and does not include the entire marsh plain. As mentioned before, pilot studies and published studies conducted for this research indicated that relatively few numbers of inbenthic faunal inhabit the marsh plain. Therefore this part of the marsh was excluded from this study.

RELATED RESEARCH

Salt Marsh Ecology

The dynamic nature of salt marsh ecosystems makes them extremely stressful to the organisms living there. Organisms living in salt marshes must be able to adapt to a wide range of salinity, temperatures, desiccation and anoxic conditions.

Food Webs

Macroinvertebrates occupy a mid-trophic level in the dynamic marsh ecosystems. The major primary producers in a typical salt marsh are *Spartina spp.*, microalgae, and phytoplankton (Pomeroy and Wiegert 1981). Marshes are detritus-based food webs where primary production starts with cordgrass, and its decay leads to bacterial growth and the high energy flow (Ranwell 1972). Bacterial and protozoan conversion of *Spartina* into food for invertebrates and fish is key to marsh fertility (Ranwell 1972). Microbial breakdown of the detritus is an important step in the transfer of detrital energy to copepods (Knox 1990). Benthic invertebrates such as clams, bivalves, decapods, worms, as well as juvenile fish feed on the copepods and bacteria and then become food for the many resident or migrant birds (Zedler 1996). In this mid-trophic level, the invertebrates are critical to the continued flow of energy in marsh ecosystems as shown in figure 1.

Benthic detritivores are grouped into three general categories: grinders and shredders (i.e. amphipods that chew detritus particles), deposit feeders (i.e. polychaetes that select particles from sediments), and filter or suspension feeders such as the bivalves. The chewing of the plant particles by the detritivores results in a decrease of detritus particle size. This increases the surface to volume ratio of the particle, which enhances the

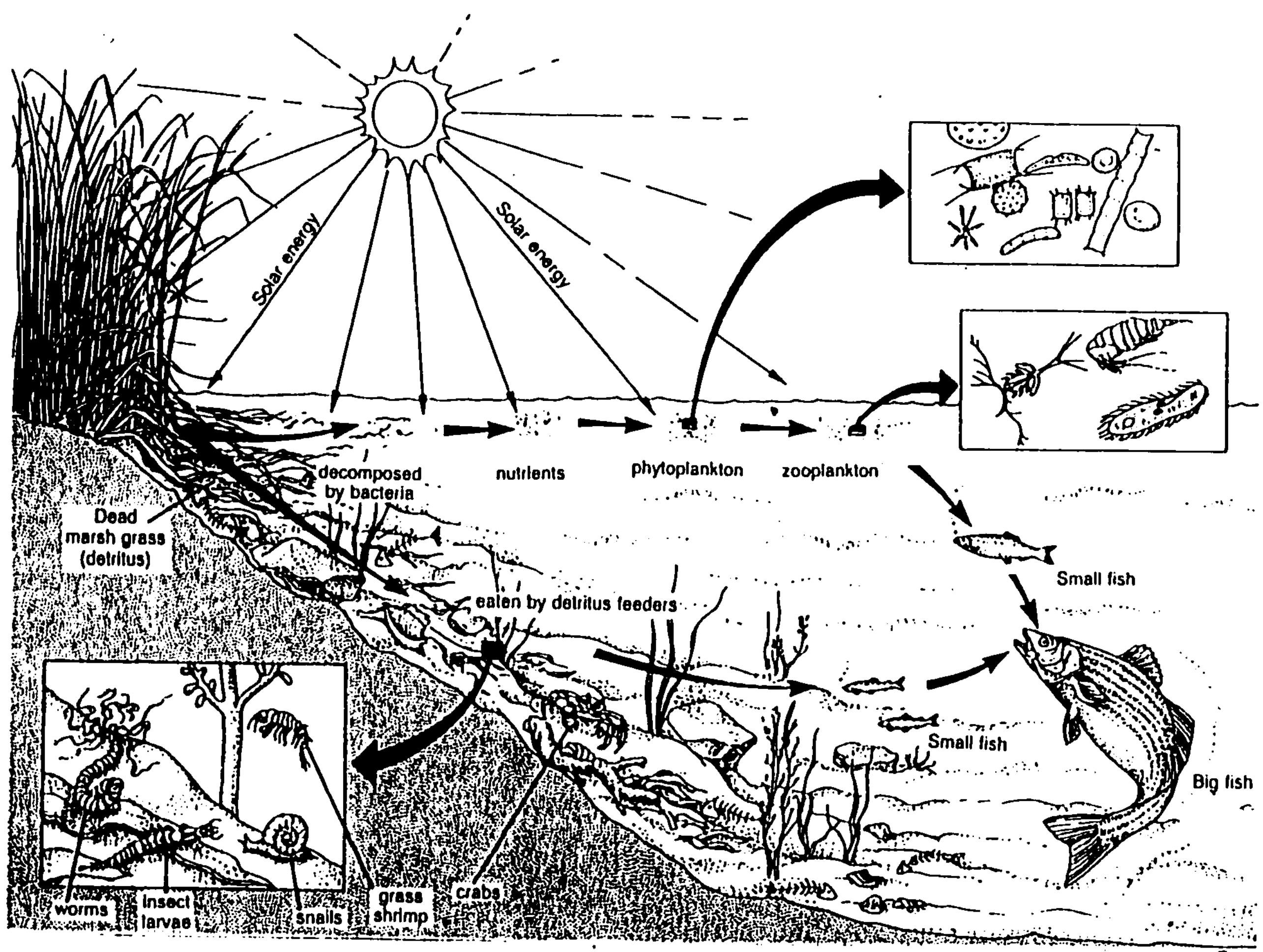

Figure 1. Diagram of a detritus food web of an estuary. Illustration from Owens, Oliver S., and Daniel D. Chiras. ed. 1995, Figure 11-8.

availability of the detritus food for microbes, thereby increasing microbial biomass. This, in turn, increases the protein content of detritus (Knox, 1990).

Population Dynamics of Benthic Invertebrates

Plankton are the food of the benthic suspension feeders, such as the clams *Gemma gemma* and *Macoma* spp., and plankton populations are extremely variable. Suspension feeders are fixed to the substratum and are unable move to more favorable feeding areas, thus, they are typically opportunists, rapidly exploiting favorable conditions and building up large populations. However, their populations fluctuate strongly over time, with dramatic population crashes occurring after their food resources have been depleted (Knox 1990).

Benthic deposit feeders, such as the polychaetes *Streblospio benedicti* and *Heteromastus filiformis*, have a relatively stable food source of either live or dead plankton, benthic microalgae, or detritus that has been deposited on the bottom of the marsh. Detritus has an attached microbial community of bacteria or micro- and meiofauna that supply protein to the deposit feeders. Deposit feeders have a greater range of food than suspension feeders, but their major food source, the organic detritus, is constantly being supplied to the sediments. According to one researcher, bacterial decomposition is the rate-controlling step on food generation that buffers deposit feeders against food fluctuations (Knox 1990).

Benthic Invertebrate Succession

Successional changes occur in benthic communities as species assemblages switch from early successional filter feeding species such as the bivalves to mature community deposit-feeding species such as the polychaetes. There is a general trend from a system first containing a "peak of opportunistic species" in a highly organic enriched environment to an "ecotone point" of low abundance and high diversity. Next, the system moves into a "transitory zone" which initially has great fluctuations in populations until, finally, it reaches the "normal" or stable populations with lower levels of nutrient enrichment (Pearson and Rosenberg 1978). Overall, there is a decrease in the ratio of filter feeders to deposit feeders, as a system develops from opportunistic to stable populations (Pearson and Rosenberg 1978).

Disturbances, such as organic enrichment or freshwater flooding, can destabilize the later successional populations leading to transitory or opportunistic type species assemblages (Nordby and Zedler 1991). Opportunistic species prevail in disturbed systems and tend to be small, rapidly breeding, short-lived, and contain a high level of genetic variability, as occurs in species such as *Capitella capitata*. There is a marked decrease in species richness with increased nutrients. Long term organic enrichment leads to a much simpler community structure composed predominately of deposit feeders (Pearson and Rosenberg 1978). One study showed that after 15 years of fertilizing salt marsh creeks, there was a shift in dominance from polychaetes to a dominance of oligochaetes (Sardá, Foreman, and Valiela 1994). Another major disturbance in salt marsh systems is the inundation of freshwater. Excessive rainfall or flooding locally decreases salinity and leads to the extirpation of many benthic species (Nichols and Pamatmat 1988; Nordby and Zedler 1991). As the environment stabilizes, community complexity will increase, eventually returning to a more stable community structure as demonstrated in figure 2 (Pearson and Rosenberg 1978).

<u>Benthic Species Affect Their Environment</u>

Benthic species may be able to influence succession by affecting their environment. Benthic macroinvertebrates are not only controlled by the environment, but they are also able to control their environment. Some of the ways this is accomplished is by filtering

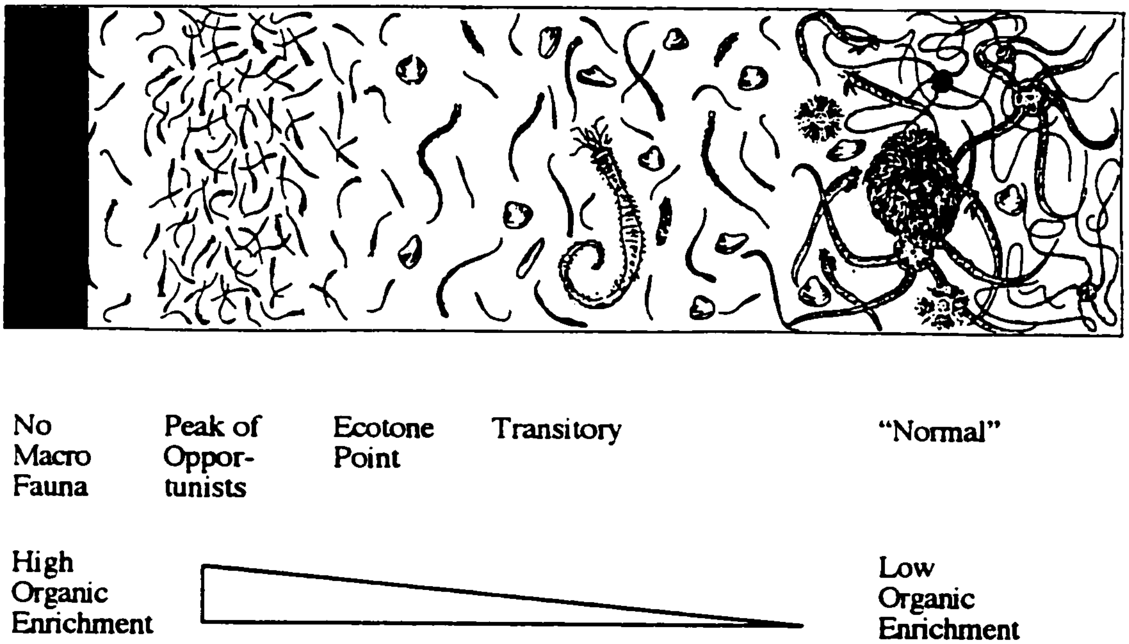

Figure 2. Macrobenthic succession in response to organic enrichment. Illustration from Pearson, T. H., and Rosenberg, R. 1978, figure 20.

water, predation and bioturbation. Filter feeding species have the capacity to purify the water, decreasing organics and lowering turbidity of the water column (Pearson and Rosenberg 1978). The benthic invertebrates prey upon zooplankton, consuming the smaller, slow moving forms such as bivalve larvae, thereby limiting the settling of these species. Bioturbation is biogenic re-working of the sediments by burrowing and churning of the substrate. This burrowing and churning mixes the mud and aerates the soils which can increase the depth of the oxygenated layer, or the redox depth. Increased redox depth changes the habitat, making it accessible for secondary species to colonize (Pearson and Rosenberg 1978).

Environmental Effects on Benthics

Redox, percent soil organics, and vegetative cover are some of the many environmental factors that are known to influence benthic communities and distribution. Other factors such as temperature are known to influence seasonal changes. Excessive heat or cold drastically reduces macrofauna abundance (Sardá, Foreman, and Valiela 1995). Daily and seasonal changes in salinity and dissolved oxygen are common in salt marshes. Salinity dictates the type of inbenthic communities encountered. Eurohaline opportunistic species, which are mostly annelids, are unable to tolerate salinity levels lower than 5 ppt., whereas estuarine endemics can often tolerate less than 2 ppt. One species of *Macoma* is known to tolerate freshwater under laboratory conditions (Knox 1990). These factors are examined in this thesis.

Redox. Redox potential discontinuity depth (RPD) is determined by the distance from the soil surface to the upper portion of the transition layer. The transitional layer is the area between the light oxidized soil on the surface and the dark anoxic soils below. RPD has been shown to be affiliated with oxygen penetration, type of successional assemblages, and the overall quality of the benthic habitat. Research has also shown that most benthic organisms tend to utilize the upper oxygenated layer, and only rarely employ the anoxic region (Rhoades and Boyer 1982). Researchers have found the RPD to be a valuable measure of habitat quality and a predictor of the presence of secondary colonizing species, which are commonly found in RPD depth of 10 - 20 cm. (Rhoades and Boyer 1982; Knox 1990).

The depth of the redox layer is known to migrate vertically in response to a variety of physical factors. Protecting the sediments from water movement such as waves, wind, stream flow, and tides decreases the amount of mixing. This will shift the redox layer closer to the surface. High temperatures can also elevate the redox layer, which can be a daily or seasonal event. Increased organic matter or enrichment also brings the level of the redox layer closer to the surface. Daylight, on the other hand, lowers RPD due to the oxidizing activity of phototrophic bacterial and algae. Bioturbation also lowers the RPD as it causes mixing and oxygenation of the sediments (Pomeroy and Wiegert 1981).

Soil organic matter. Organic matter is another important physical factor in salt marshes. Several studies have determined that natural marshes contain higher organic matter content than constructed marshes (Minello and Zimmerman 1992; Levin, Talley, and Hewitt 1998). These studies found positive correlations between the percent organic matter and the infaunal composition and abundance. Organic matter provides the basis of the marsh food web. Minello and Zimmerman (1992) hypothesize that this higher species abundance is because organic matter contributes to the process of microalgae production. Organic matter is also speculated to provide shelter or support for some burrowing species (Netto and Lana, 1997; Levin, Talley, and Hewitt 1998).

Netto and Lana (1997) found that vegetation in *Spartina* marshes plays a key role in macrobenthos distribution. They found below-ground and dead above-ground biomass were the parameters most highly correlated to high macrobenthos densities. The below ground fraction may provide refuge and physical support for tube builders and may provide anchoring for bivalves. Studies done by Lana and Guiss (1992) also suggest live plant material is predominantly used by some species for refuge or physical support rather than a food source.

Vegetation effects. There are differences in opinion as to the effects that vegetation has on benthic communities. Some studies report higher infaunal densities in *S. anglica* vegetated areas than in adjacent mud flats, although species richness did not vary (Jackson 1985). Kalejta and Hockey (1991) reported higher species densities on mud flats. At least two studies have found mud flats to be species-poor (Mason, Heath, and Gibbs, 1991; Netto and Lana 1997). One California study found macrofaunal densities similar between mud flats and *S. foliosa* vegetated areas, but species richness was higher on mud flats. These differences could be due to regional differences in inundation times, percent organic matter in the soils, salinity or greater below ground vegetation that could inhibit burrowing (Levin, Talley, and Hewitt 1998).

Vegetation to inbenthics relationship studies have been done on South African and South American marshes. Netto and Lana (1997) found composition of benthic communities varied with respect to below ground biomass and dead above ground vegetation. Kalejta and Hockey (1991) studied a South African estuary where they examined correlations between individual species and vegetation. They found at least two species positively correlated with vegetation, the polychaete *Capitella* spp. and the gastropod *Hydrobia*. *Capitella* spp. was especially correlated to algae cover suggesting its opportunistic habits. One nerid worm, *Ceratonereis* spp. was negatively associated with vegetation or presence of algae. Overall they found species densities the highest on mud flats.

Another species-habitat study, done by Sardá, Foreman, and Valiela (1995), correlated different soil sediment types of unvegetated mud flats to inbenthic production. Highest production was reported on sandy organics. Dominant species were the polychaetes *Marenzelleria viridis*, *Capitella capitata*, *Neanthes succinea*, *N. arenaceodonta*, *Polydora ligni*, *Heteromastus filiformis* and the oligochaete *Lumbricillus* sp. These researchers reported that muddy sites had a relatively low production value. The species that were highly correlated to the muddy areas were *Streblospio benedicti* and oligochaetes. All of the above mentioned studies show that environmental parameters do affect inbenthic distribution.

Successional Studies on Created Marshes

Several studies have examined the successional stages in newly created marshes (Cammen 1976; Zajac and Whitlatch 1982; Levin, Talley, and Thayer 1996). Levin, Talley, and Thayer (1996) studied benthic invertebrates in southern California and east coast *Spartina* marshes. They found that although macroinvertebrate densities and species richness of constructed marsh resembled the reference marshes in 6 months, species composition and faunal feeding modes differed. These researchers found that natural marshes contained a greater number of surface and subsurface deposit feeders and fewer carnivores than reconstructed marshes. This suggests that there may be functional differences between the two marsh types.

Spartina marshes are known to contain the opportunistic *Streblospio benedicti*, *Capitella* spp., and *Polydora* spp. triad (Zajac and Whitlatch 1982; Levin, Talley, and Thayer 1996). In SF Bay, *Capitella* spp. are considered irruptive species, where a population irrupts only when conditions are favorable and specimens are not always found in all samples or even found from year to year (Nichols and Pamatmat 1988). The main opportunistic species found in early successional or disturbed sites in the SF Bay are *Capitella* spp., *Gemma gemma*, and *Ampelisca abdita*. Opportunistic species often have a planktonic larval stage that enables them to colonize quickly over a wide dispersal area.

Levin, Talley, and Hewitt (1998) found *S. benedicti* is the dominant species in older, reference marshes and numbers are often lower in newly prepared or disturbed soils. *Streblospio benedicti* were most commonly found in mud flats, but mud flats also contained more polychaete, crustacean, and molluscan taxa than the adjacent salt marsh. *S. benedicti* numbers can exceed reference marshes in some new marshes in the first few years, but after 4 years a difference may no longer be seen. Overall, Levin, Talley, and Hewitt (1998) found reference marshes contain 35% *S. benedicti* and 45% oligochaetes.

Levin, Talley, and Hewitt (1998) found that oligochaetes and cirratulids were late colonizers of marsh soils. Oligochaetes were rare in marshes younger than 4 years. Cirratulids did not begin to colonize until after 27 months before becoming abundant. These researchers believe oligochaetes to be an indicator of mature marshes. Oligochaetes do not have a planktonic dispersion phase and individuals must colonize from nearby areas. Levin, Talley, and Hewitt (1998) found oligochaetes more common in Southern California marshes than in East coast marshes. *Spartina alterniflora* marshes supported more tubificid oligochaetes and fewer enchytraeids than *S. foliosa* sediments. Little is known about the ecological importance of this class of organisms. Their high number and differing taxonomic classification between the East and West coast marshes suggests the need for further research into their ecology to enhance the knowledge of marsh function.

The differences seen in Pacific versus Atlantic marshes by Levin, Talley, and Hewitt (1998), suggest care in comparing the two systems. Researchers must question to what extent they can apply studies from one marsh system to solve practical problems of another. Therefore, it may not be possible to fully apply *Spartina* marsh ecology from other locations to SF Bay marshes. A more complete knowledge of our SF Bay marshes is needed in order to adequately manage or restore these systems.

Factors Influencing Succession

Levin and others found several factors that may influence succession. The first is the timing of the newly constructed marsh. If the construction occurs during a rapid recruitment time, there may be a more rapid colonization than if construction occurs during the slow fall recruitment time. Size of the habitat and marsh configuration are other determinants. Edge effects were demonstrated to be important by Minello, Zimmerman, and Medina (1994). Higher abundance and diversity was reported in areas where artificial channels were created.

Continuity with natural systems as a nearby source of colonization was an extremely important factor in the rapid colonization of the marshes (Levin, Talley, and Thayer 1996; Kusler and Kentula 1990). Not only the proximity of a natural marsh, but the maturity of the adjacent natural marsh was important in the type of species that colonized. Levin, Talley, and Thayer (1996) recommended accelerating the colonization rates by seeding marshes with taxa that disperse poorly and providing the habitat requirements of the benthic invertebrates.

Although soil properties are found to be important in several studies, they are not a focus of this research.

Use of Benthics for Ecological Assessments

In the past, marsh restoration projects have primarily focused on plant cover (Zedler 1996). Epibenthic invertebrates, species living on marsh surfaces, have only recently been used as yardsticks to measure the success of marsh restoration projects. Benthic invertebrates in particular can be useful for habitat assessments due to their sessile nature and mid-trophic position in the marsh food chain (Varanasi et al. 1993). The sessile nature of benthics limits their ability to move away from poor quality habitats and therefore they are directly affected by habitat conditions. The mid-trophic level position provides information on marsh primary production as it relates to density of benthics and makes them a good predictor on the status of higher trophic level consumers.

Mason, Heath, and Gibbs (1991) found faunal richness was not related to floral diversity. Faunal recovery was much slower than plant cover. Minello and Zimmerman (1992) also found that marsh benthics developed slower than plant cover and related benthic abundance to the buildup of organic matter. Even five years after construction, restored marshes had insufficient time to reach equivalency with older marshes in their ability to provide food for the higher trophic level species.

Common Invertebrates in San Francisco Bay

Most inbenthic studies on salt marshes have been completed on the East coast marshes, and many of the organisms found in the East coast salt marshes are not found in the SF Bay. Nichols and Pamatmat (1988) have been surveying the benthic component throughout the SF Bay for decades, although they do not focus on the salt marshes in particular. They have found that the overwhelmingly dominant invertebrates in the intertidal and shallow subtidal areas of the southern portion of San Francisco Bay are *Gemma gemma* (gem clam, a filter feeder), *Ampelisca abdita,* (Amphipod, a filter and deposit feeder) and *Streblospio benedicti.* Other common mollusks species include *Macoma balthica* (Baltic clam, a native species), a surface deposit feeder and filter feeder, *Mya arenaria* (soft-shell clam), a filter feeder, *Tapes phillipinarum* or *japonica* (Japanese littleneck clam) a filter feeder, and *Mytilus edulis* (bay mussel, possibly a native species). Some of the longer living species include *Eteone spp.* and *Nereis procera,* a carnivorous predatory nerid worm (Nichols and Pamatmat 1988; Pittman 1996).

Most species found in the San Francisco Bay are rapid colonizers and are indicator species of organic pollution. They are tolerant of high organic levels and anoxic conditions and thrive in marginal areas around zones of high pollution. Organisms such as *Capitella* spp., *Streblospio benedicti, Nereis* spp, *Neanthes succinea, Macoma balthica, Mytilus edulis,* and *Mya arenaria*, can all be found on polluted mud flats (Pearson and Rosenberg 1978). Species such as *Capitella* spp., *Mya arenaria* and *Corophium* spp., are thought to be irruptive species. This is demonstrated by the irregular distribution of *Capitella* spp; they are often not found in benthic surveys (Nichols and Pamatmat 1988).

Over the past 150 years or so, the San Francisco Bay has undergone great transformations in its benthic infaunal component. At least 200 species of invertebrates have been introduced from the Pacific rim, Australia, Chile, and the Atlantic coasts. Most of these introductions are limited to the estuarine bay and lagoon environments (Carlton 1975). Benthic species in the southern portion of the San Francisco Bay are thought to be greater than 80% exotics (Nichols and Pamatmat 1988). Exotic invertebrate species are constantly being introduced into the San Francisco Bay by cargo ship ballast water and intentional or unintentional introductions. One exotic bivalve, *Potamocorbula amurensis*, the Asian clam, was introduced in 1986 and is now commonly found throughout the bay. This prolific species is believed to have led to the decline of at least 3 copepod species by predation (Kimmerer, Gartside, and Orsi 1994). The introduction of *P. amurensis*, although an ecological disaster, has resulted in greater study of the benthos-pelagic interaction.

The relatively young age of the Bay contributes to the successful introductions of so many exotics (Carlton 1975). A stable native community may not have developed leaving many ecological niches open. There are relatively few bays and estuaries on the West coast, and these are often widely separated hindering the development of a diversified endemic community. Extensive dredging and filling may have modified Bay habitats enabling exotic species to colonize.

METHODS

Study Site Selection

All study sites were located in the southern portion of the San Francisco Bay, California, as shown in figure 3. The study sites were arranged in a paired design with each pair consisting of a reference marsh and a restored marsh within one mile of each other. Four pairs of marshes were selected for the study with the constraints that the marshes were fully tidal, water flow was not restricted by culverts, the reference marsh was between 15 and 150 years of age and the restored marsh was between 10-20 years. Most restoration sites in this study were once salt evaporation ponds.

Background on Study Sites

Don Edwards San Francisco Bay National Wildlife Refuge, Fremont, California

Don Edwards San Francisco Bay National Wildlife Refuge consists of 5,500 acres in the Fremont unit of the larger San Francisco Bay National Wildlife Refuge (SFBNWR). SFBNWFR consists of 22,000 acres owned by the US Department of Interior, Fish and Wildlife Service (FWS). Adjacent land is owned by the Cargill Salt Company which still maintains salt ponds for production (Sverdrup & Parcel Associates 1985). Site locations are shown in figure 4.

Reference site: Newark Slough. (Size sampled: approximately 10 acres. Age: over 150 years). The Don Edwards (DE) reference site is bordered by Newark Slough to the east and a levee that restricts a salt evaporation pond to the west. This thin strip of marsh area adjacent to Newark Slough has been minimally altered by the building of hunting

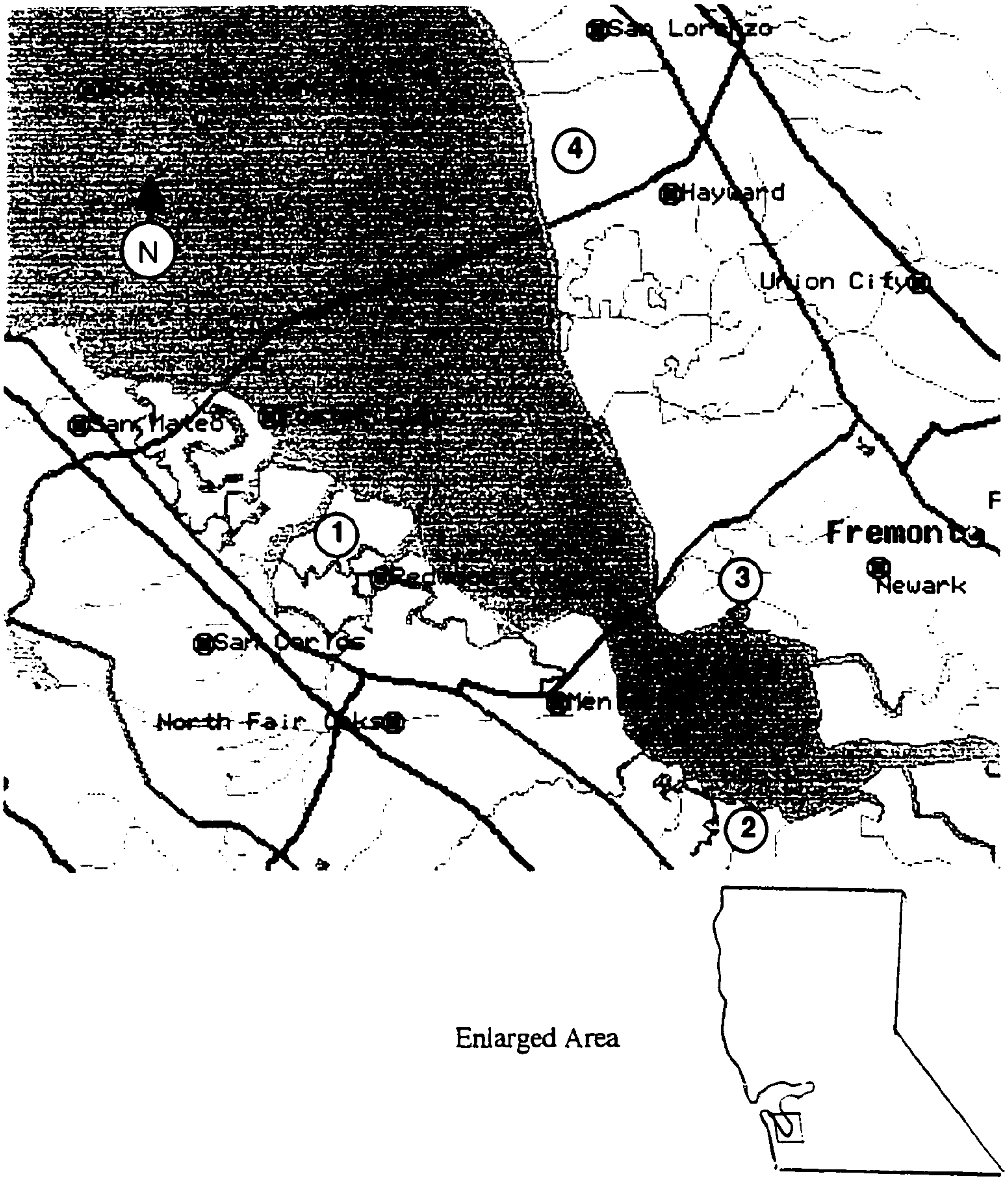

Figure 3. General site location map: 1, Bair Island (BI), Redwood City; 2, Shoreline Regional Park (SRP), Mountain View; 3, Don Edwards (DE) San Francisco National Wildlife Refuge, Fremont; 4, Hayward Area Recreation District (HARD), Hayward. Scale: 1:228583, centered at Lat [illegible] 7557 Lon: -122.153. Source: http//tiger.census.gov.

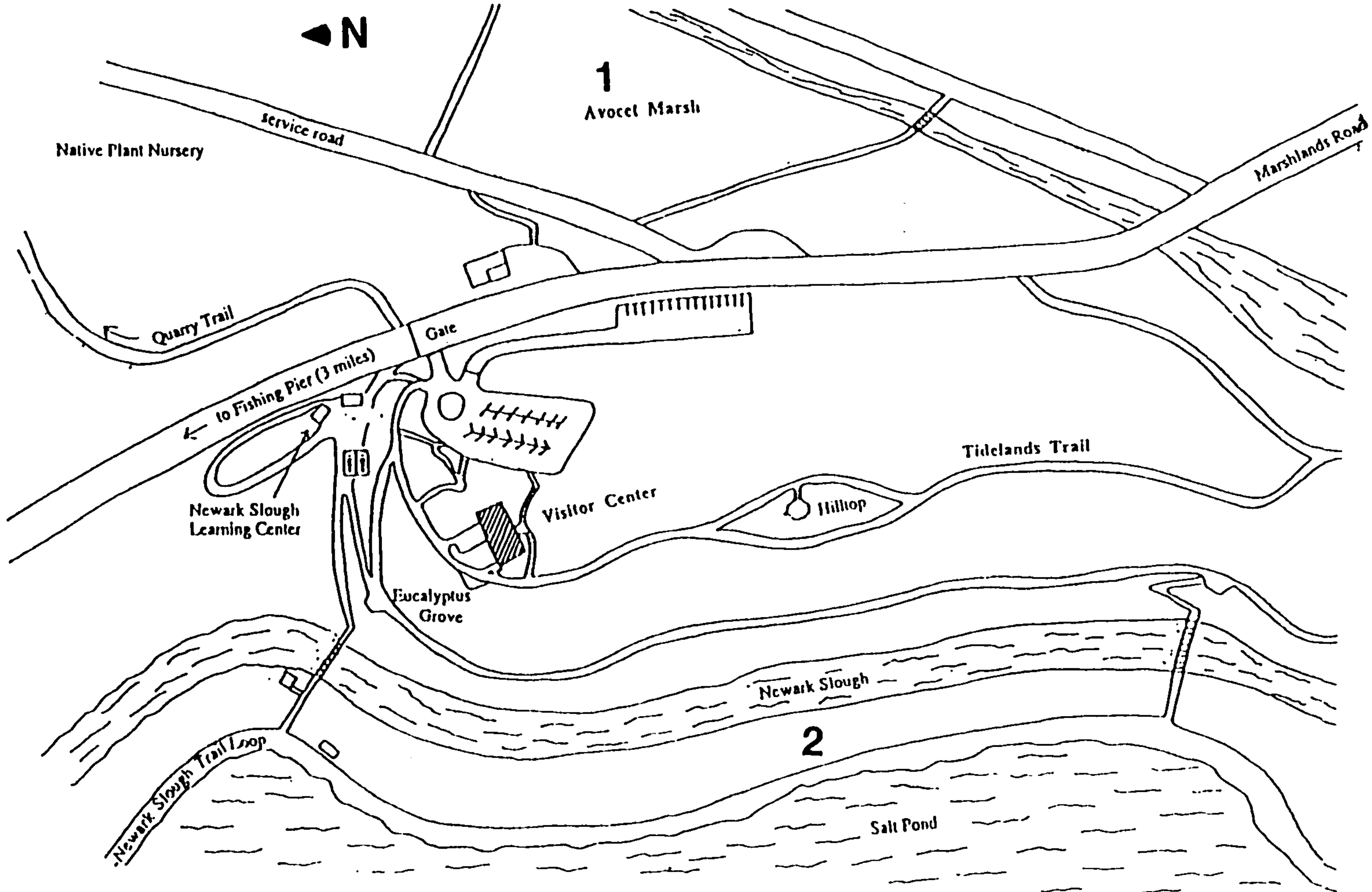

Figure 4. Don Edwards (DE) site map: 1, restored site; 2, reference site. Source: Don Edwards San Francisco Bay National Wildlife Refuge trail map.

lodges and bridges over the slough. Its size has been severely restricted by levees and roads (Kimmy 1998). Surrounding land uses are salt evaporation ponds, Highway 84, and the national wildlife preserve.

Restoration site: Avocet Marsh. (Size sampled: approximately 6 acres. Age: approximately 10 years.) Known as either Tract 102 or Avocet marsh, the Don Edwards (DE) restored site consists of 134 acres that was once part of the Cargill Salt Company (previously Leslie Salt). The site was used as evaporation ponds between 1948 and 1979, until Cargill abandoned it in 1979 (Sverdrup & Parcel Associates 1985). Before being a salt pond, it may have been marsh or dry land (Kimmy 1998). Approximately 10 acres of Avocet marsh were sampled that contained a more developed wetland due to a greater amount of tidal action. It is bordered by a hill to the west that is part of the preserve area, and a levee to the east that is used for hiking. Levees surround the site on all other sides. Some of these levees once separated salt evaporation ponds, but are now used as hiking trails and they separate recovering marsh areas. Other levees separate the marsh from urban development such as roads and an industrial park (Kimmy 1998). This marsh was allowed to naturally regenerate beginning in 1988 by breaking levees to allow tidal flow and disking or leveling of the landscape (Joy Albertson, Wildlife Biologist, personal communication, February, 1997).

Hayward Area Recreation Department (HARD), Hayward, California

(Site locations are shown in figure 5.)

Reference site: San Leandro creek mouth. (Size sampled: 2-4 acres, Age: approximately 15 years.) This site is located directly on the San Francisco Bay at the headwaters of San Leandro creek in the city of San Lorenzo. It is bordered by the Bay to the west, and a levee to the east that separates it from human development. This extremely narrow strip of land is actually a naturally forming marsh with no human intervention. It

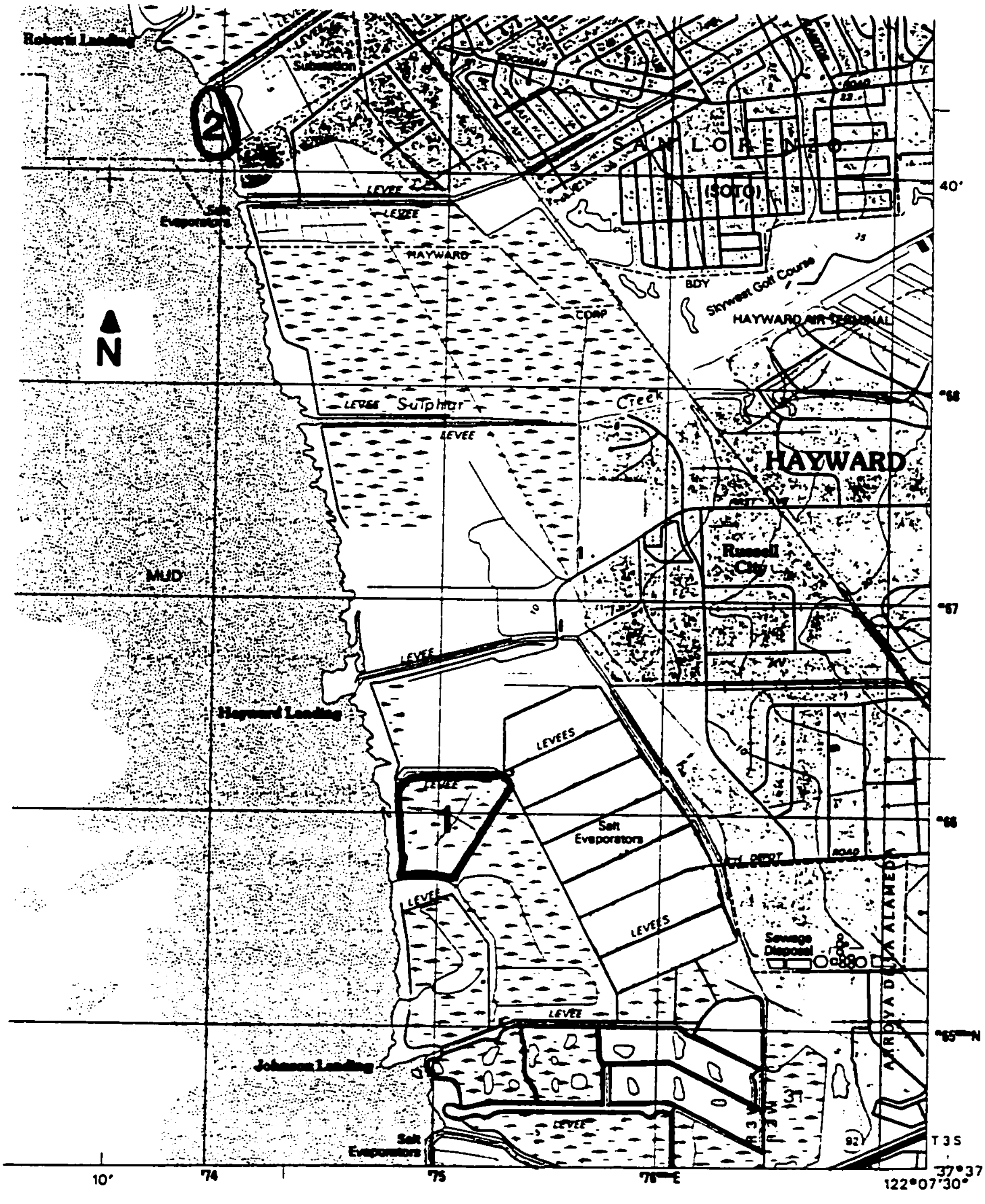

Figure 5. Hayward Area Recreation District (HARD) site map: 1, restored site; 2, reference site. Source: USGS San Leandro Calif. quadrangle, 7.5 minute series topographic. 1:24,000 scale, photo reduced.

has been forming for approximately 15 years (Kimmy 1998). Tidal flushing comes directly from the Bay. Number of acres: 2-4

Restored site: Cogswell Marsh. (Size sampled: approximately 20 acres, Age: approximately 17 years). Known as Cogswell marsh, this site is bordered by the San Francisco Bay to the west, a waste disposal facility to the North, and levees in the other two directions. These levees separate it from other recovering marshes. This site was restored in 1982 by breaking the levees, and planting cordgrass. Tidal flushing comes directly from the Bay. Active management is practiced at this marsh to control exotic plants such as the Atlantic cordgrass, *Spartina alterniflora* (Mark Taylor, Site Manager, personal communication, February, 1997).

Bair Island, Redwood City, California

Bair Island (BI) Ecological Reserve sites are owned by the State Lands Commission (SLC) and leased to the Department of Fish and Game (DFG). It is known as one of the largest uninterrupted wetland ecosystems in the Bay Area. Three federally listed endangered species are known to inhabit the area such as the California clapper rail (*Rallus longirostris*), the California least tern (*Sterna albifrons*), and the salt marsh harvest mouse (*Reithrodontomys raviventris*) (Trulio 1997). Managers have implemented the Bair Island Ecological Reserve Management and Operations Plan produced by Josselyn in 1991. Site locations are shown in figure 6.

Reference site: Corkscrew Slough. (Size sampled: approximately 20 acres, Age: over 150 years). This site is considered a pristine, historic wetland, and is bordered to the north, east and south by Corkscrew Slough. A levee to the south separates it from an abandoned salt evaporation pond. It is believed to have never been diked or modified (Trulio 1997).

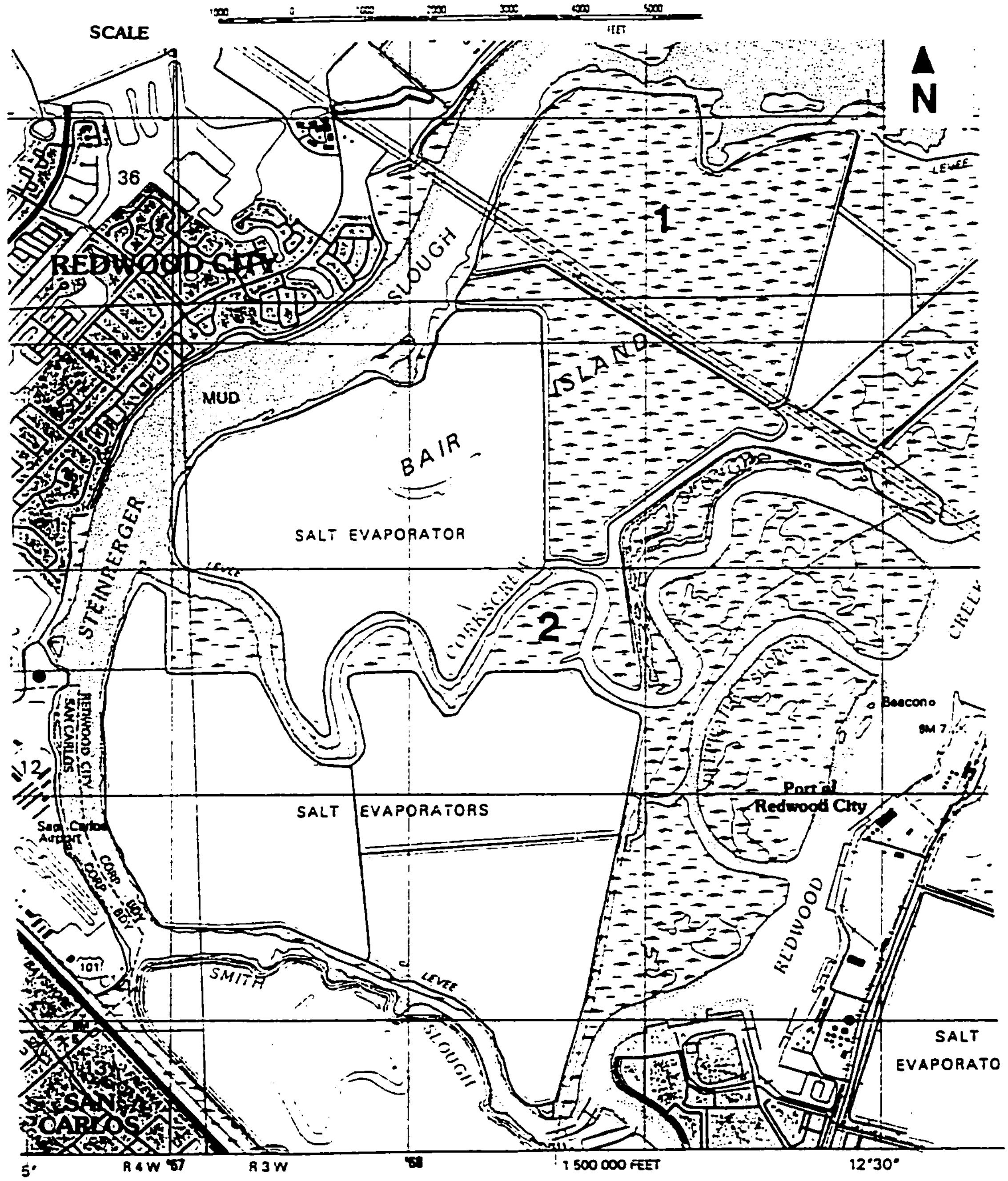

Figure 6. Bair Island site map: 1, restored site; 2, reference site. Source: USGS Redwood Point Calif. quadrangle, 7.5 minute series topographic. 1:24000 scale, photo reduced.

Restoration site: Department of Fish and Game. (Size sampled: approximately 20 acres, Age: approximately 17 years). Adjacent to SF Bay on west side, levees restrict this marsh in all other directions from salt evaporation ponds. The east levee is the area where the samples were collected near a catwalk built and maintained by the Pacific Gas and Electric Company. Once a salt evaporation pond, a levee naturally broke in the late 1970s which resulted in restoration of the site. This marsh is the largest of the sampling sites covering 300 acres (Trulio 1997).

Shoreline Regional Park (SRP), Mountain View, California

Shoreline At Mountain View is a regional recreation and wildlife area. There is a commitment to improve habitat for endangered species as well as educational purposes. This site was going to be developed into an amusement park in 1970s, turning an eyesore of a junkyard, hog farm and a sanitary treatment plant into a theme park. The former wetlands had all been diked or filled. However in 1972, the Bay Area residents and governmental agencies became concerned with environmental effects of this type of development. Eventually the original development of rides, hotels, and tramways became golf courses, a sailing lake, and interpretive hiking trails. Part of the mitigation for this development required salt marsh restoration (Wittenberg 1990). Site locations are shown in figure 7.

Reference site: Outer Charleston Slough. (Size sampled: approximately 20 acres, Age: over 150 years). This site, called Outer Charleston Slough, lies adjacent to Charleston Slough, the SF Bay to the north. Two levees separate this site from other wetland areas. These levees are used as biking and hiking trails. Charleston Slough flows in from SF Bay and ends on the outside of the culvert that separates it from inner Charleston slough area.

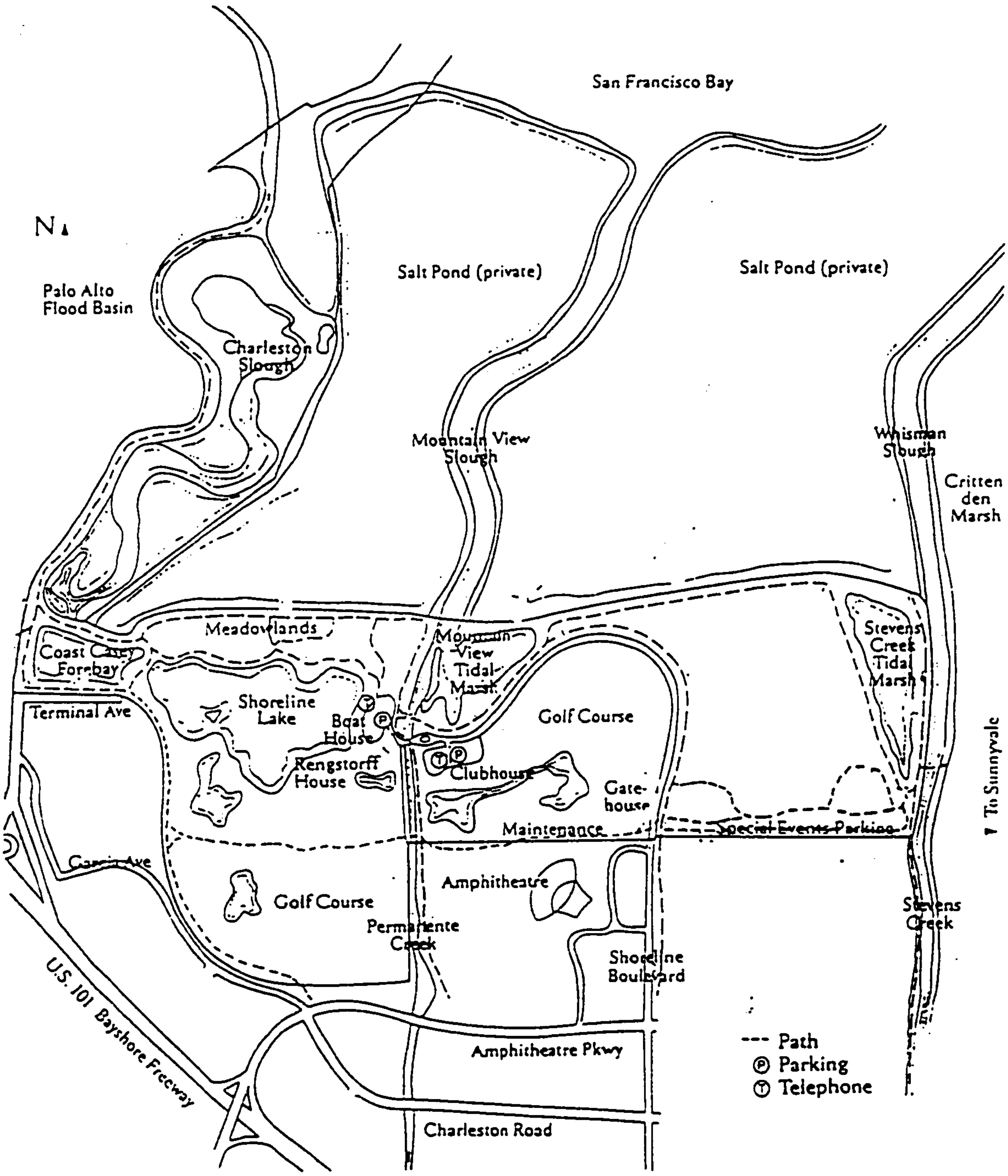

Figure 7. Shoreline Regional Park (SRP) site map; 1, restored; 2, reference. Source: Shoreline-at-Mountain View trail map.

Restoration site: Mountain View Tidal Marsh. (Size sampled: approximately 20 acres, Age: approximately 16 years). This site is fed by Mountain View Slough, but is restricted by levees on all sides. There are 3 breaks to the west side levee where tidal waters enter the marsh. Restoration work began around 1982. The area was planted with native cordgrass, *Spartina foliosa*, to speed colonization of this marsh plant. Pickleweed, on the other hand, was allowed to establish on its own from seed flowing in on the tidal waters (Wittenberg 1990). It is surrounded by levees with hiking trials.

Pilot Study

A pilot study was conducted one month prior to the main study, between May 27 and May 30. This work was done to obtain initial data on which species inhabit the study sites. This information aided in the determination of inference limits to avoid unnecessary sampling. Five core samples were collected per site during this initial phase. See "Inbenthic distribution sampling" section in this chapter for core dimensions. The results of this study indicated an abundance of inbenthic species in the tidal channels, and a lack of inbenthics in areas of high percentage *Salicornia* cover at higher marsh elevations. A large number of epibenthic fauna were collected at this higher elevation, such as gastropods and amphipods. Since this group of animals was not the focus of this study, the marsh plain areas were eliminated from this study and only the marsh tidal channels habitats were examined. Other researchers have also noticed an increased usage of organisms in the tidal channels. Minello and Zimmerman (1992) created artificial channels in marshes and reported an abundance of animals utilizing the newly created edges as compared to the inner marsh.

Data for water quality profiles such as temperature, salinity and dissolved oxygen, were also collected approximately one month prior (May 27-30) and again approximately two weeks prior (June 11-14) to the main study. Water quality profiles were also collected during the main study (June 24-28). Pilot testing was done to establish ranges and medians for the parameters that vary over time. These habitat parameters are indicative of the surroundings in which the benthic organisms feed. For methods on how these parameters were collected see "Environmental parameter sampling" section later in this chapter.

Random Sampling Strategy

The random sampling strategy for the full study was developed by first mapping the tidal channels in each marsh. Distances for each tidal channel were paced off and every pace given a unique number in sequence and charted on the map. If a channel could be accessed from either side, then each side of the channel was considered in the randomization scheme and given a unique number. The total number of paces was added for each marsh separately. This number supplied an upper limit for random number generation later. Random numbers were generated using the SYSTAT program. The numbers generated were then located on the map and these locations were used to collect core samples and habitat data.

Inbenthic Distribution Studies

Core samples were obtained during June 24-28, 1998. Late spring or early summer core sampling is the preferred method for population studies of benthic invertebrates (Zajac and Whitlatch 1982; Sardá, Foreman, and Valiela 1995). Methods similar to those used in Kalejta and Hockey (1991) and Pittman (1996) were incorporated. Random points between the elevations of 0 - 3 ft National Geodetic Vertical Datum

(NGVD) at each of the 4 sites were selected as described above. This elevation consists of the low to middle intertidal zones of the salt marshes (Ricketts and Calvin 1985; Pittman 1996). The soil samples were collected during the low and mid tide cycles. Once the sampling location was found, a soil core sample was extracted and environmental data were collected.

Hand-held coring devices were used to collect 15 cores from each site for a total of 60 cores from restored sites and 60 cores from the reference sites. The coring device used was a 8 cm (0.05 m^2) diameter stainless steel hot water pipe that was 30 cm long. Cores were collected to a depth of 20 cm. A one meter wooden handle was attached to the side for ease of extraction. The coring device also contained a tight fitting plastic lid to create a vacuum when extracting the cores.

The coring device was pushed into the mud and the cap was pressed on securely to create a vacuum. The core was loosened using a circular motion, then pulled straight up. The soil sample was then removed from the coring device, placed in a 1 gallon ziplock bag, and stored in a cool dark place until could it be washed. Samples were washed within 24 hours after collection.

Once the soil samples were obtained, they were carefully washed under gently running water, so as not to injure the soft-bodied animals. They were first washed through a 0.5 cm primary screen, then ultimately through a 0.5 mm tertiary screen. To release the animals remaining on the screen, the screen was gently back washed. Sieve size of 1 - 0.5 mm is the size cut-off defined for macroinvertebrates, and it is important to use this in population studies so as to not miss smaller individuals. All of the animals and resultant organic debris were collected in a mason jar and preserved in 70% isopropyl alcohol with 0.0006% Rose Bengal stain. They were stored in this solution in a dark place until the samples could be analyzed.

For the volume debris determination, sample volume was brought up to 240 ml in tap water. The volume of the wet debris was recorded after a brief settling time.

Vegetative Cover

To determine percent plant cover in the sampling area, plant species were first identified in a circle approximately 0.5 m diameter around the core. The percent cover was a visual estimation. The reason for taking into account an area greater than the actual core is that some areas contained a low percent cover, but the actual core sample may or may not have contained living plant material. Percent cover was estimated visually for each parameter: pickleweed (*Salicornia pacifica*), cordgrass (*Spartina foliosa*), other plant species and bare mud. *Salicornia* and *Spartina* were the most dominant plant species found. Other plant species were salt grass (*Distichlis spicata*) and *Jaumea carnosa*.

Sediment and Water Sampling

Soil and water quality was sampled at each station. Measurements for temperature, salinity, dissolved oxygen, pH, and redox potential depth (RPD) were obtained using portable instruments.

Temperature and salinity were measured using one instrument, the Yellow Springs Instrument Co. (YSI) Model 33 S-C-T battery powered transistorized meter (YSI inc., Yellow Springs, Ohio, 45387). This instrument measures salinity, conductivity and temperature. The probe is a plastic conductivity cell and a thermister temperature sensor all combined into a single shaft. This probe was inserted into a channel with flowing water or by using gentle agitation in stagnant water to obtain accurate readings. Temperature was measured in °C, accuracy ± 0.1- 0.6. Salinity was measured in parts per thousand (ppt.), accuracy at ±0.7 ppt.

To measure dissolved oxygen, a YSI57 meter was used with the YSI 5739 field probe attached. This measures oxygen in mg/L from 0-20 mg/L in three ranges, 0-5, 0-10, and 0-20. Generally, either the 1-5 or 0-10 range was used (Accuracy ± 1% of range, so the 0-5% range has an accuracy of ±0.05%).

To measure pH, a strip of colorphast® pH paper (EM Science, 480 Democrat Road, Gibbstown, N.J. 08027), ranging from pH 6 to 9 in increments of 0.5 units, was dipped into the nearest water source. The pH paper was compared to the color charts on the package after waiting approximately two minutes.

To measure redox potential depth (RPD), a clear 5 cm acrylic tube was inserted into the ground adjacent to the core sample. The tube was covered with a cap to create a vacuum that enabled the core to be extracted from the soil. Depth of the oxygenated layer can be seen as a light brown layer overlaying a darker gray or black anaerobic layer. The top brown layer was measured to the nearest 0.5 cm.

Quantifying Animals

For identification and quantifying animal species, first the larger *Macoma spp.* and *Neanthes spp.* were removed from the washed core sample and counted. This number was then divided by 4 for equalizing the data, as only 25% of each core was subsequently screened. With continual vigorous stirring, 60 mls were removed for observation and counting. This sample was then diluted as necessary in tap water for easier identification of the animals. Approximately 5 mls of sample could be examined at a time under a Bausch and Lomb dissecting scope with 7-30X magnification. Rose Bengal stained animals were removed, identified to the lowest possible taxonomic classification, and counted.

The eight most dominant species were selected for analysis. These were chosen based on 3 criteria. First they had to represent more than 1% of the total population, next they had to be positively identified, and finally, they had to be found in more than 25% of the sites. Because of difficulty in identification, oligochaetes were identified only to the family level and nematodes to phylum level.

Data Analysis Methods

Data were analyzed on two different spatial scales, Micro and Macro. To examine species and habitat characteristics on a micro-scale, observations for analyses were from individual cores or areas surrounding individual cores. For macro-scale analysis each site was considered as a whole; all the values for cores from a particular site were averaged together to obtain a site average.

Micro-scale Invertebrate to Environment Correlation

Multivariate Canonical Correlation analysis (Tabachnick and Fidell, 1996) was used to determine if there were any correlations between environmental parameters and abundance of species on a micro-scale. Six dominant invertebrate species and six environmental parameters were included in the analysis (because of small sample size, only 12 parameters could be analyzed). The invertebrate species used in the correlation were: the bivalve ***Macoma baltica***, three polychaetes species; ***Neanthes succinea***, ***Heteromastus filiformis***, and one unidentified sedimentary (possibly a juvenile) polychaete A, Nematodes, and one oligochaete. Higher order taxa in this group were treated as a single taxonomic unit, as they were difficult to identify. Two species were eliminated in this correlation due to low loadings or low representation. These were the polychaetes *S. benedicti* and *E. lighti*. The environmental parameters used in the correlation were temperature, salinity, redox, pH, percent bare mud cover, and volume of organic debris. Some parameters were eliminated due to low loadings, such as dissolved oxygen and percent plant cover.

Micro-scale Environmental Factor Descriptions (PCA)

Physical factors, including salinity, organic carbon content, RPD, type of vegetation cover and soil particle size, were analyzed using the multivariate principle components analysis (PCA). Then, the factor scores were used as input for independent t-tests to test for potential differences between the restored and reference sites (Tabachnick and Fidell 1996). The HARD sites were eliminated from the factor score t-test because both HARD sites are new, developing marshes. The reference marsh is not an old undisturbed marsh, but a naturally forming marsh with no human intervention.

Macro-scale Similarity Determination (MDS)

To determine degree of similarity in species composition of benthic invertebrates among sites, Bray-Curtis Similarity Index values were computed between all possible pairs of sites and subsequently analyzed with Multidimensional Scaling (MDS) (Tabachnick and Fidell 1996). The formula for the Bray-Curtis similarity index is:

$$\frac{2*\sum Min(X_{ik},X_{ij})}{\sum(X_{ik}+X_{ij})}$$

X_{ik} and X_{ij} represent each measured parameter in the sites to be compared. Data were log(x) transformed prior to analysis. The invertebrates used in the MDS were the same ones used in the canonical correlation, but also included the polychaetes *Eteone lighti* and *Streblospio benedicti*. Due to sample size, all of the invertebrates examined could be used in the MDS similarity index.

The Bray-Curtis Similarity index and MDS were also used to examine degree of similarity in habitat characteristics among sites. This technique was also used for habitat similarity using the means of each environmental parameter per site. The habitat parameters examined were the same ones used in the canonical correlation, such as temperature, salinity, pH, redox, percent bare mud cover, and volume of organic matter, but also included dissolved oxygen and the percent plant cover observations.

Macro-scale Abundance to Diversity Correlation

Volume of organic matter, percent abundance of oligochaetes and polychaetes, and species evenness, were correlated to each other using the Pearson Product Moment Correlation Coefficient (Witte and Witte 1997). Diversity was computed for each site using the Shannon-Weaver diversity index: $H = -\sum p_i \ln p_i$, where p_i is the proportion of each species. Species evenness (J) was determined by $J = H/H_{max}$, where $H_{max} = -s\ln s$, and s is the total number of species found. Percent species composition was determined by the total number of one species per site by the total number of individuals found at that site times 100.

RESULTS

Taxa Examined

A total of 29 taxa were observed in this study as listed in appendix A. This analysis was limited to polychaetes, oligochaetes, bivalves and nematodes. Crustaceans, gastropods, isopods, and insects are epibenthic species and were not considered or counted in this study. Some bivalves, oligochaetes, and polychaetes were not considered due to low representation, low distribution, or because they were unidentifiable. One unidentifiable polychaete species, that was probably a juvenile , was used in the analyses. This organism was found in high numbers and is labled as "polychaete A". The eight most dominant, identifiable species examined in this study were five polychaete species (*N. succinea*, *S. benedicti* , *H. filiformis*, *E. lighti* and polychaete A), 1 species of oligochaete, 1 species of bivalve, *M. baltica*, and nematodes. There were at least 3 unidentified species of oligochaetes and one unidentified species of polychaete. Two species of polychaetes not included in the study were cirratulids and *Polydora* spp. The bivalves observed but not included due to low representation were *Gemma gemma*, *Mya* spp., and *Ischadium demissum*. Species that were observed but not counted were at least 3 species of gastropods, 2 species of insect larvae, a pseudoscorpion, one isopod species, crustaceans such as Ostracods, Cumacea, and gammerids (at least 3 species: *Corophium* spp., *Orchestia* spp. and one unidentified species).

Micro-results

Canonical Correlation

Canonical correlations found 2 significant roots. Loadings for both of these canonical roots are given in table 1 on page 53. Root 1 found a 65% correlation (r_{c1}=0.65, p<0.001) as displayed in figure 8 on page 54. A positive correlation was seen between high abundances of oligochaetes to low redox potential depth, low salinity, low temp, low volume of organic matter, low percent plant cover and slightly basic pH. These physical conditions generally characterize young marshes. High abundance of nematodes and polychaete A correlated to high redox, high salinity, higher temperatures, high volume of organic matter, high percent plant cover and neutral pH, typical parameter values for older marshes. Root 2 was also significant (p<0.001) with a 57% correlation and is shown in figure 9 on page 55. In this root, high abundance of *Macoma* spp. *Neanthes* spp. and *Heteromastus* spp. correlate to low percent plant cover, low redox and neutral pH. High abundance of polychaete A correlate to high redox, high percent plant cover and a more basic pH.

PCA Habitat Ordination

PCA analysis found four factor components that explained more than 10% of the variance. Factor loadings are given in table 2 on page 56, and an ordination of factor1 versus factor 2 is displayed in figure 10 on page 57. Factor 1 explained 24% of the variance, factor 2, 17%, factor 3, 12%, factor 4, 11%. Independent t-tests on the PCA factors revealed a significant difference between reference and restored marshes in factor 2 when the HARD sites were eliminated (p=0.002). The HARD sites were eliminated because they are both new marshes and do not have an older reference marsh for comparison. The HARD reference marsh is used as a standard for 10 year old naturally forming marsh to see how it compares with 10 year old restored marshes. The t-test result would signify that most reference sites had high factor 2 scores and contained high salinity, low percent cordgrass cover, high pickleweed cover, neutral pH, high volume of organic matter, low temperatures and low dissolved oxygen. Restored sites tended to have lower factor 2 scores with low salinity, high percent cordgrass cover, low pickleweed cover, more basic pH, low volume organic matter, higher temperatures and higher dissolved oxygen content.

The ordination of factor 1 versus factor 2 showed BI sites clustering in same quadrant with high factor 1 and 2 scores. This quadrant represents high redox, and salinity, lowest of highs in dissolved oxygen, percent cordgrass cover and temperature. It also represents the highest of highs in percent pickleweed cover and volume of organic matter. These sites also have low percent open areas and more neutral pH.

DE restored samples were predominantly in the quadrant with high factor 1 scores and low factor 2 scores. This site was similar to the BI sites habitat characteristics except that pH was slightly higher and salinity was lower. This site had the highest dissolved oxygen, percent cordgrass cover and temperature. Although the ordination places this site with high volume organic matter and high redox, it is actually fairly low in these parameters.

HARD restored site samples are predominately in the quadrant with low factor 1 scores and high factor 2 scores. This site is best represented a high percent bare mud and high salinity. It has neutral pH, low temperature, dissolved oxygen and percent cordgrass cover. It has a low percent pickleweed cover and volume organic matter.

Shoreline restored core samples were found mostly in quadrant 3 which have low scores of factor 1 and 2. This site can best be represented by low salinity, high percent cordgrass cover, low percent pickleweed cover, more basic pH, low volume of organic matter, high temperature, and low dissolved oxygen.

The other sites; DE reference, HARD reference, and SRP reference sites lie in between factor 2 scores, therefore, these sites are best explained by low factor 1 scores. These sites represent a high percent bare mud cover, low redox (except SRP reference site is fairly high), low dissolved oxygen (except HARD reference site is fairly high), low percent cordgrass cover (although HARD reference and SRP reference sites are fairly high), low percent pickleweed cover, low volume of organic matter (except DE reference site is fairly high), and low temperature (except DE reference site is fairly high).

Macro-results

MDS Similarity

Bair Island sites were very similar to each other with respect to invertebrate diversity and abundance, and environmental parameters. The Don Edwards reference site was very different from the restored site in both the invertebrate and habitat similarity studies. Shoreline sites were weakly similar in habitat characteristics but dissimilar with respect to the infaunal component. HARD sites were also found to be weakly similar habitats but dissimilar in the faunal component. Dimension loadings for both invertebrate and environment are shown in table 3 on page 58.

Invertebrate MDS

Invertebrate ordination is displayed in figure 11 on page 59. This ordination shows the two Bair Island sites clustered in the MDS quadrant containing low scores in dimension 1 and 2. These sites contain a high abundance of *H. filiformis, S. benedicti, N. succinea, E. lighti* and the lowest of the high *Macoma*, but contain a the highest of the low abundance of polychaete A and oligochaetes. These sites also contained the highest diversity.

The DE reference and HARD restored sites had low dimension 1 scores but high dimension 2 scores. These sites were the next most diverse sites and contained high

Heteromastus, *S. benedicti*, *N. succinea*, *E. lighti*. and oligochaete abundance, as well as the highest of the high *Macoma* spp. abundance, and lowest of the low polychaete A abundance.

The Shoreline reference site had a high dimension 1 score and a low dimension 2 score. This site contained low *H. filiformis*, *S. benedicti*, *N. succinea*, *E. lighti* and *Macoma* abundance, high polychaete A abundance, low oligochaete abundance, and the highest of low *Macoma* abundance.

HARD reference, SRP restored and DE restored sites clustered in the quadrant of high dimension 1 and 2 scores. These sites contained a low abundance of *H. filiformis*, *S. benedicti*, *N. succinea*, *E. lighti* and *Macoma*, high oligochaete abundance, highest of the low *Macoma* abundance and lowest of the high polychaete A abundance. These sites also had the lowest diversity.

Environment MDS

The environment ordination is displayed in figure 12 on page 60. This ordination shows the Bair Island sites were very similar with respect to habitats and had high scores in both dimension 1 and 2. These sites contained a high percent cordgrass cover, low percent bare mud areas, high dissolved oxygen, high redox, neutral pH, high volume of organic matter, high percent pickleweed cover, highest redox potential depth, and high salinity and temperature.

The Don Edwards sites are very different from each other with respect to habitat characteristics. The Don Edwards reference site is more similar to the Bair Island sites with a low dimension 2 score, but dissimilar in dimension 1 scores. This site is best characterized by having a low percent cordgrass cover, high percent bare mud, low dissolved oxygen content, highest of the low redox depth, and slightly basic pH. It is similar to BI sites in dimension 2 by containing a high volume of organic matter, high percent pickleweed cover, and high salinity and temperature.

HARD restored site was similar to the DE reference site with low dimension 1 scores but similar to its restored site with high dimension 2 scores. This site is similar to DE reference site by containing a low percent cordgrass cover, high percent bare mud, low dissolved oxygen, low redox, slightly basic pH. It is dissimilar to DE reference and more similar to its reference site and SRP sites by containing a low volume organic matter, low percent pickleweed cover, and low temperature. Although this ordination puts this site at low salinity it is actually fairly high.

DE restored site is similar to HARD reference site and both SRP sites with high dimension 2 scores, but similar to both BI sites with high dimension 1 scores. This site contains a high percent cordgrass cover, low percent bare mud areas, high dissolved oxygen, neutral pH, low volume of organic matter, low percent pickleweed cover, the lowest of high redox, and low temperature and salinity.

HARD reference site clustered with both the Shoreline sites. These sites varied in their habitat type and their dimension 1 score was situated near zero, therefore their habitat characteristics are best represented by dimension 2. These sites can be characterized by containing a low volume of organic matter, low percent pickleweed cover, low redox, low temperature, relatively low salt and dissolved oxygen, and slightly basic pH.

Infaunal Composition

<u>Abundance Results</u>

Inbenthic abundance was found to be higher in restored sites, that averaged between 59 and 92 and individuals per core, as compared to their reference sites, that averaged between 35 to 67 individuals per core. Figure 13, on page 61, displays the means of infaunal abundance per site. The sites containing the highest to lowest infaunal abundances were; HARD restored, DE restored, BI restored, HARD reference, SRP restored, BI reference, SRP reference, and DE reference. Two species, an oligochaete and polychaete A, comprise nearly 70% of the total infaunal abundance found in this study.

Percent Species Composition

Examining the percent composition of oligochaetes, polychaetes, bivalves, and nematodes showed reference sites to contain 43% oligochaetes, 51% polychaetes, 3% bivalves, and 3% nematodes. Restored sites contained 46% oligochaetes, 44% polychaetes, 2% bivalves, and 8% nematodes. Both of the HARD sites are newer marshes between 10 and 15 years old. The reference marsh is a newly forming marsh, with no human intervention. Since they are both new marshes, they are comparable to restored marshes, but are not characteristic of older marshes, therefore, the HARD marshes are often removed from analyses that compare older with newer marshes. When the HARD sites were eliminated from the compositional studies, then the percent oligochaetes in reference sites decreased to 26%, polychaetes increased to 67%, bivalves increased to 4%, and nematodes decreased slightly to 2%. Restored sites changed little with the removal of the HARD data and were found to contain 44% oligochaetes, 43% polychaetes, 2% bivalves, but nematodes increased to 11%. *Streblospio benedicti* made up 14% of the abundance of organisms in all marshes. Reference sites contained 16% *S. benedicti*, and restored sites contained 13%. Removing the HARD sites from the composition studies showed that the percent of *Streblospio benedicti* in reference sites jumped to 20%, and restored sites decreased to 4%. Figure 14, on page 62, shows the percent species composition by site age, and demonstrates that higher species evenness is found in older marshes. Figure 15, on page 63, shows percent polychaete composition by sites, and that older marshes tend to have a higher percent of polychaetes than newer marshes. Figure 16, on page 64, shows percent oligochaetes by site and indicates that newer marshes tend to have a higher composition of oligochaetes than older marshes.

Diversity and Pearson Correlation Results

The Bair Island sites contained the highest species richness, evenness and diversity as shown in table 4 (pg. 65). Figure 17, on page 66, displays species evenness by site. The Don Edwards reference site and the HARD restored site were the next highest in species richness, evenness and diversity. The DE reference site had a good diversity of animals, but lacked abundance. SRP reference and DE restored sites were fairly low in species richness, diversity and evenness. These sites tended to be dominated by oligochaetes and/or polychaete A. HARD reference site was very low in species diversity and evenness. Although the HARD reference site had low diversity and evenness, species richness was high. All eight species examined were seen at this site. Lowest species richness, diversity and evenness was found in the SRP restoration site. The SRP restoration site and the HARD natural sites were dominated by oligochaetes.

Pearson correlation found that diversity and evenness to be highly correlated to volume organic matter ($r = 82\%$), as seen in table 5 on page 67. Oligochaete abundance was negatively correlated to volume organic matter ($r = -70\%$). Percent abundance of oligochaetes was negatively correlated to evenness ($r = -79\%$). Percent polychaete abundance was only loosely associated to evenness ($r = 55\%$) and volume organic matter ($r = 51\%$). Percent oligochaete to percent polychaete abundance showed a strong negative association ($r = -90\%$). Overall abundance was moderately correlated to oligochaete abundance ($r = 59\%$). Figure 18, on page 68, shows the mean volume organic matter per site.

Table 1

Canonical Correlation Root Loadings

Root 1

Environment	Loading	Invertebrate	Loading
Temperature	0.389	*N. succinea*	0.062
Salinity	0.506	*M. baltica*	-0.241
pH	-0.412	*H. filiformis*	0.183
Redox	0.737	Nematode	0.682
% Bare Mud	-0.305	Oligochaete	-0.577
Vol. Organic Matter	0.377	Polychaete A	0.407

Root 2

Environment	Loading	Invertebrate	Loading
Temperature	-0.003	*N. succinea*	0.564
Salinity	0.241	*M. baltica*	0.669
pH	-0.322	*H. filiformis*	0.553
Redox	-0.420	Nematode	-0.033
% Bare Mud	0.767	Oligochaete	-0.272
Vol. Organic Matter	0.112	Polychaete A	-0.658

Loading values below |0.3| do not explain enough variance for interpretation and therefore are not used in the interpretaion of the ordination.

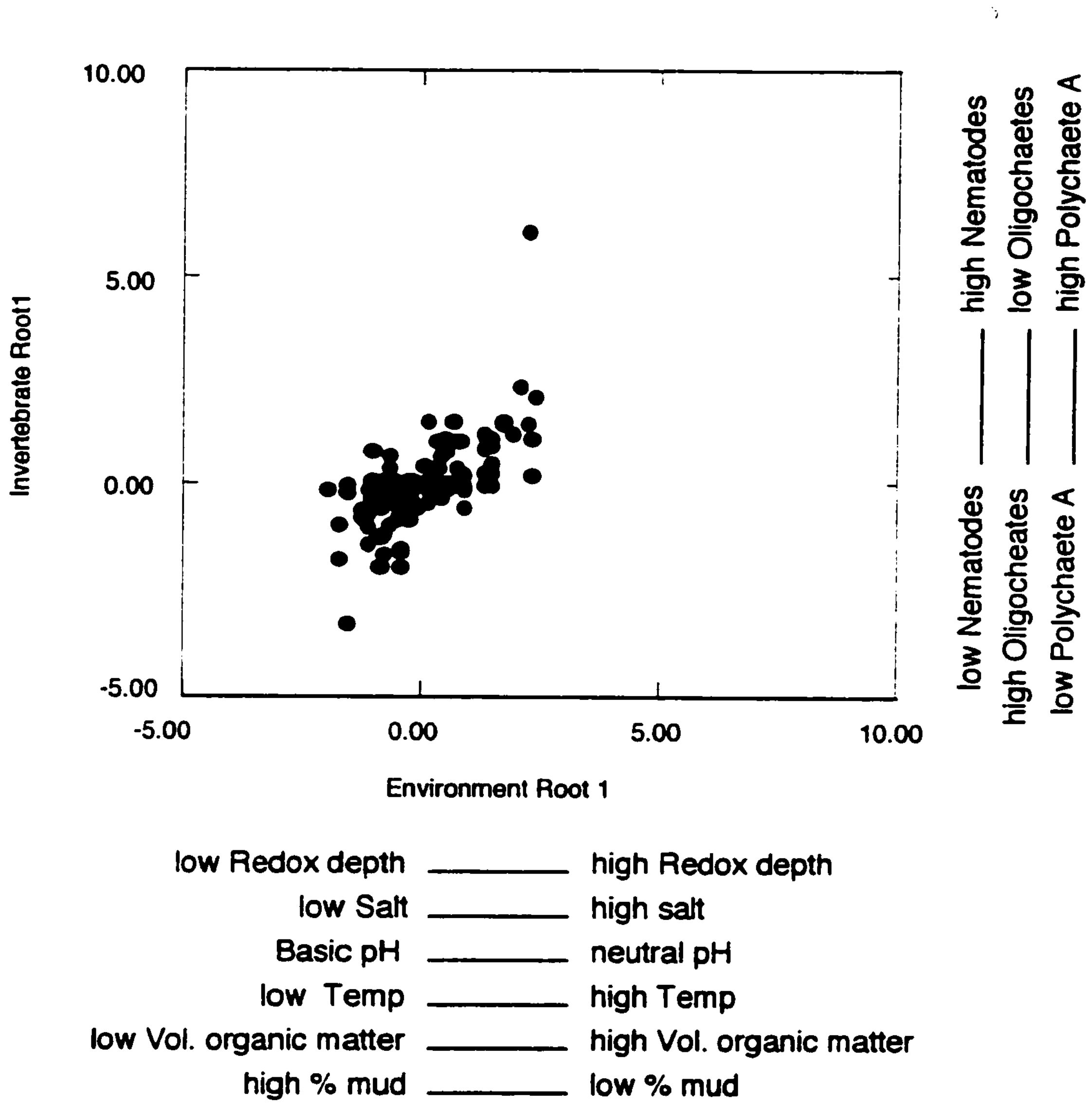

Figure 8. Canonical correlation root 1 ordination ($r_{C1} = 0.65$, $p < 0.001$).

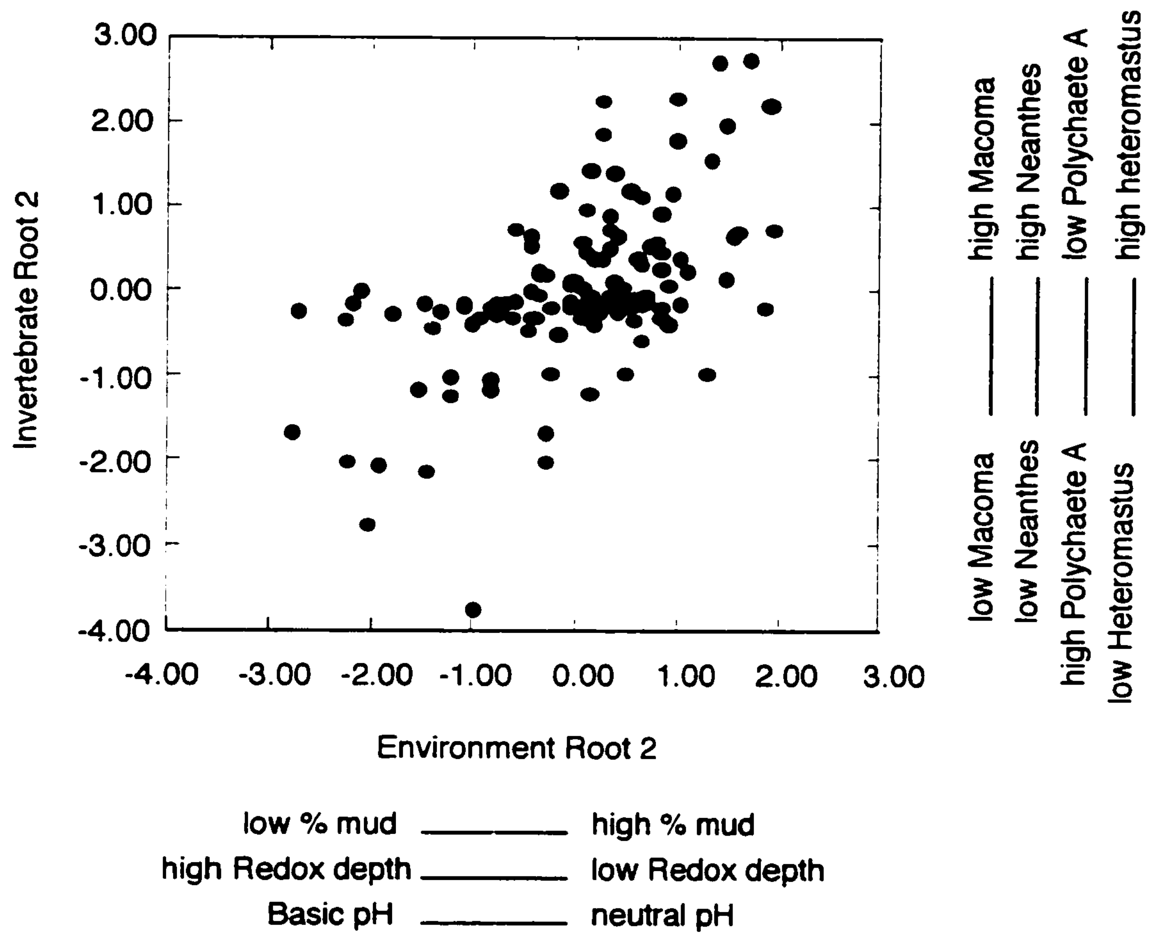

Figure 9. Canonical correlation root 2 ordination ($r_{c2} = 0.57$, $p < 0.001$).

Table 2

Principle Components Analysis Factor Loadings

Parameter	Factor 1	Factor 2
Temperature	0.403	-0.354
Salinity	-0.043	0.615
Dissolved Oxygen	0.589	-0.353
pH	-0.186	-0.491
Redox	0.653	0.202
% Pickleweed	0.454	0.512
% Cordgrass	0.545	-0.513
% Bare Mud	-0.862	0.024
Vol. Organic Matter	0.454	0.467

Factor scores below |0.3| do not explain enough variance and are not considered in the interpretation. Independant t-test showed a significant difference between restored and reference sites in factor 2 ($p=0.002$), when the HARD sites factor scores were eliminated from the analysis

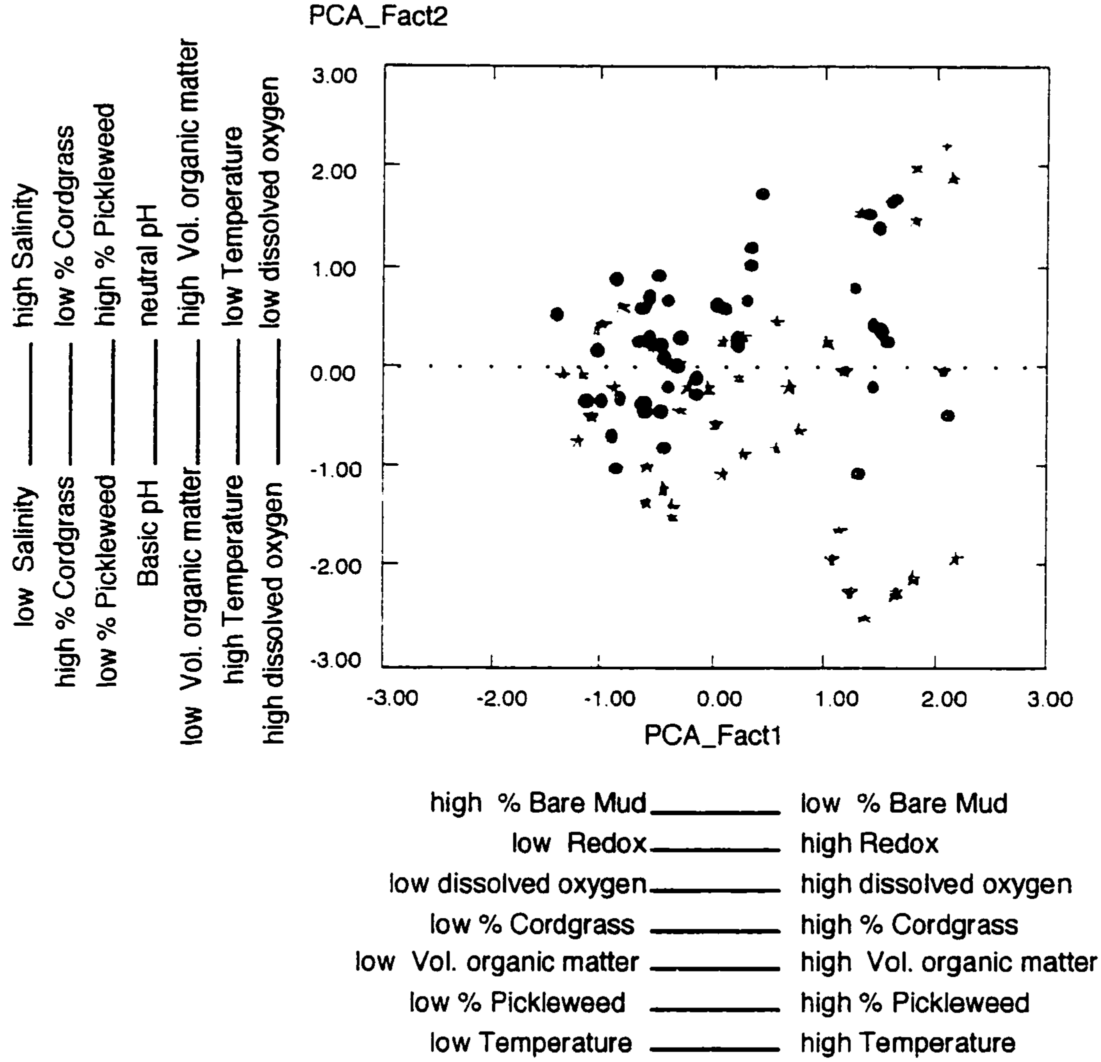

Figure 10. Priciple component analysis ordination without Hayward sites.
● = reference marshes; ★ = restored marshes.

Table 3

Multidimensional Scaling Loadings

Envionmental Parameter	Dimension 1	Dimension 2
Temperature	0.087	-0.538
Salinity	0.198	-0.379
Dissolved Oxygen	0.790	-0.316
pH	-0.350	0.319
Redox	0.495	-0.621
% Picklweed	0.278	-0.713
% Cordgrass	0.975	0.201
% Bare Mud	-0.863	0.257
Vol. Organic Matter	-0.136	-0.898

Invertebrate Parameter	Dimension 1	Dimension 2
N. succinea	-0.867	-0.276
Macoma spp.	-0.663	0.413
S. benedicti	-0.896	-0.011
H. filiformis	-0.940	-0.185
Nematode	-0.286	-0.190
Oligochaete	0.234	0.827
Polychaete A	0.622	-0.567
E. lighti	-0.840	-0.140

Dimension scores below |0.3| do not explain enough variance and are not used in the interpretation.

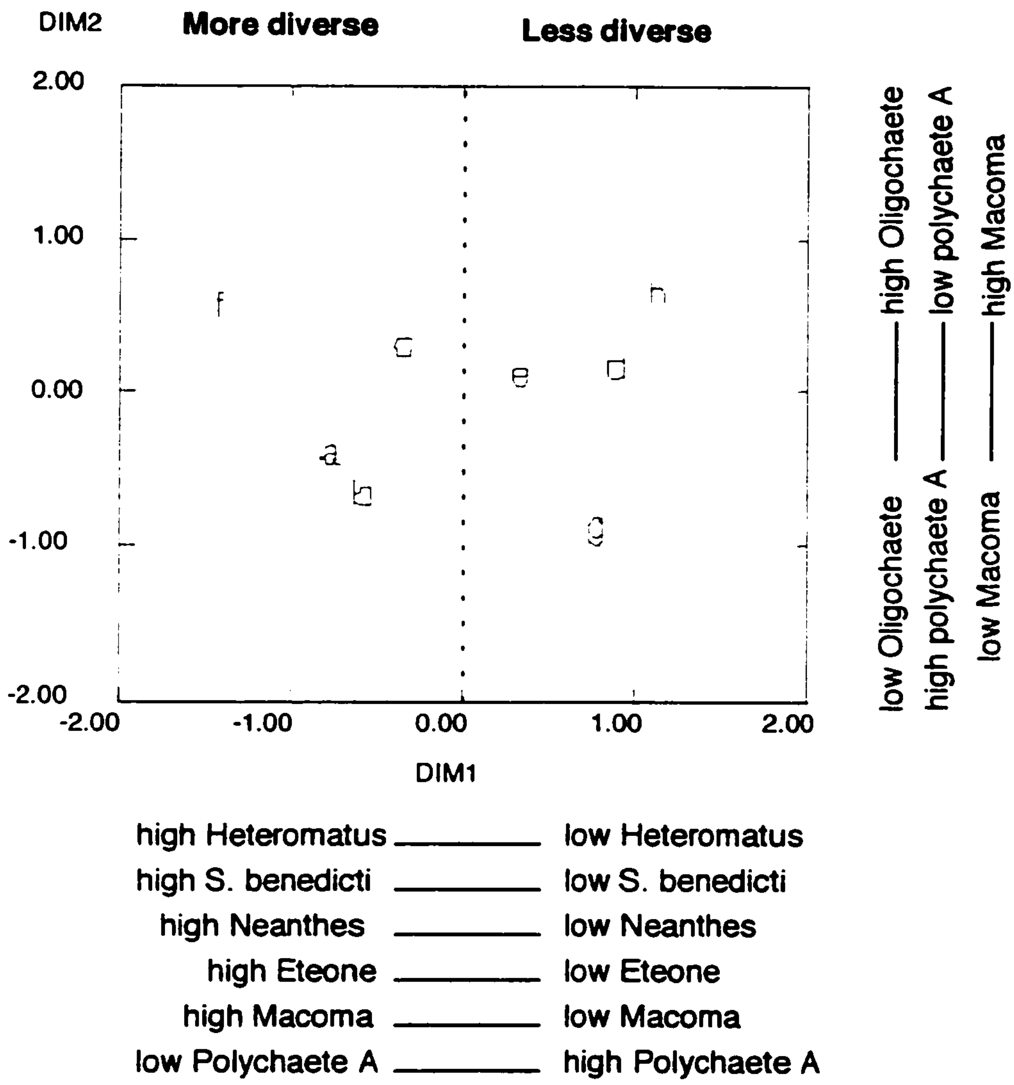

Figure 11. Invertebrate similarity MDS ordination: a, BI reference; b, BI restored; c, DE reference, d, DE restored; e, HARD reference; f, HARD restored; g, SRP reference; h, SRP restored

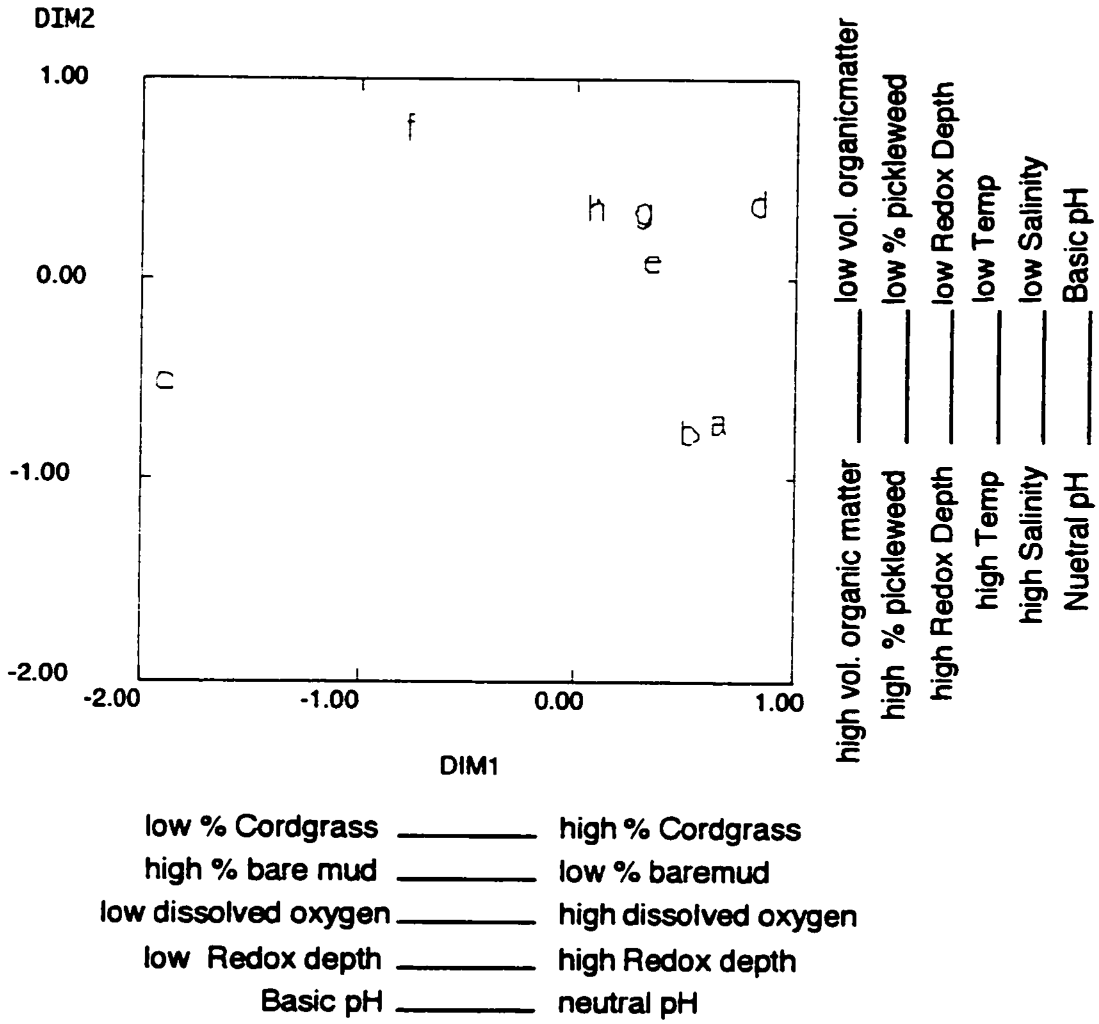

Figure 12. Environmental similarity MDS ordination. a, BI reference; b, BI restored; c, DE reference; d, DE restored; e, HARD reference; f, HARD restored; g, SRP reference; h, SRP restored.

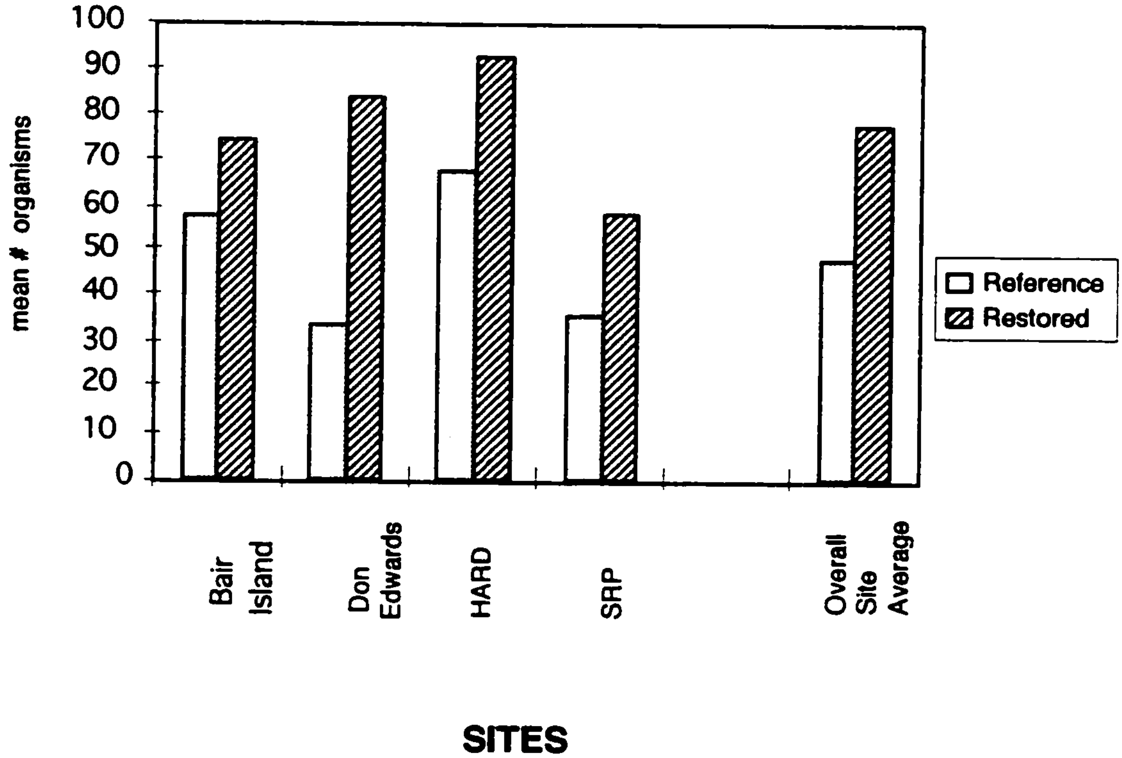

Figure 13. Average species abundance per core displayed by site.

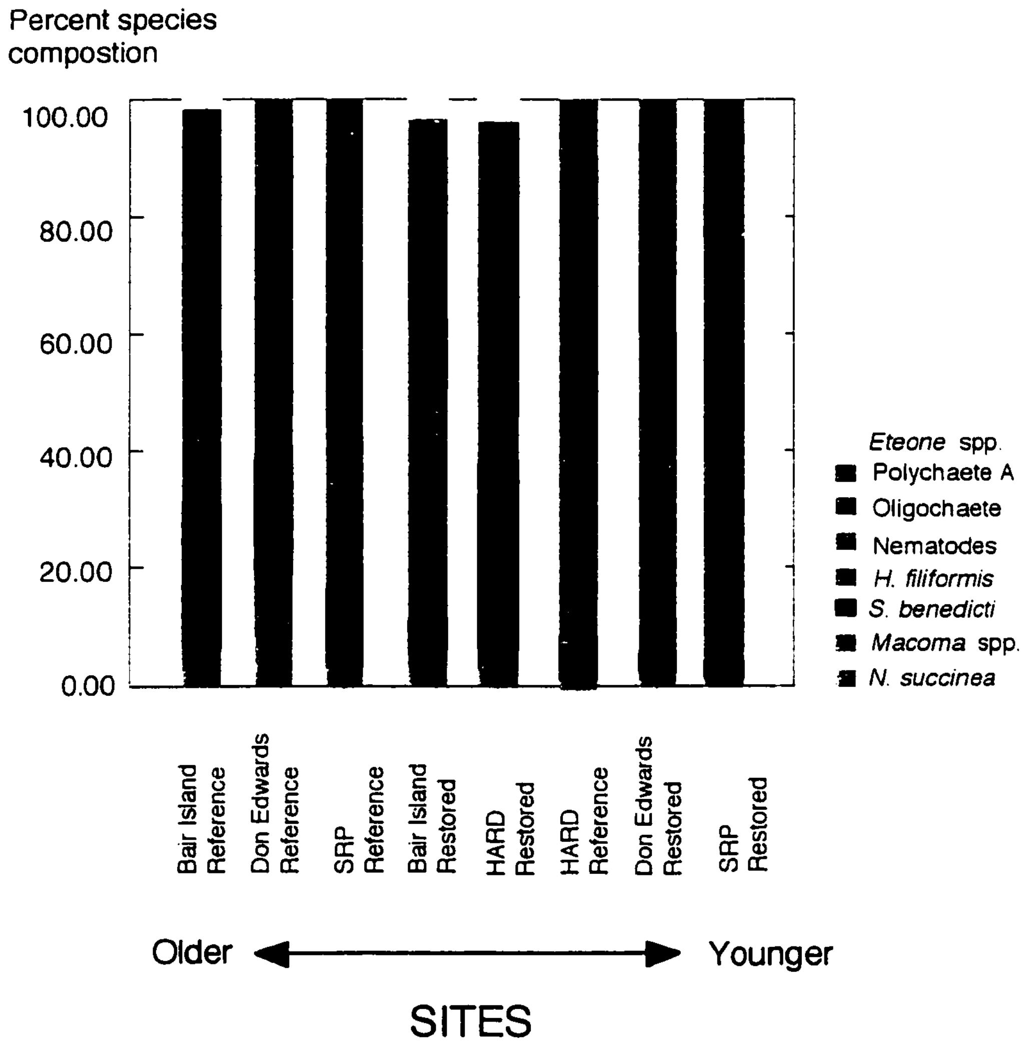

Figure 14. Percent composition of invertebrate species by site age.

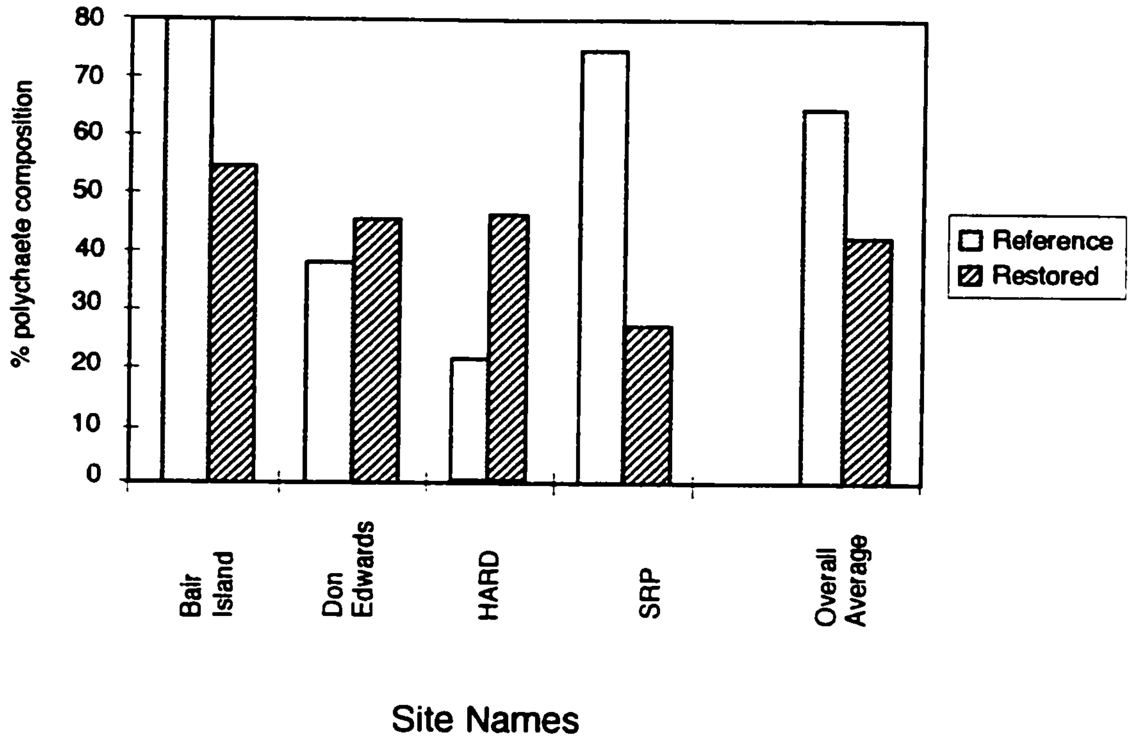

Figure 15. Percent polychaete composition by site. The overall average is calculated without the HARD sites.

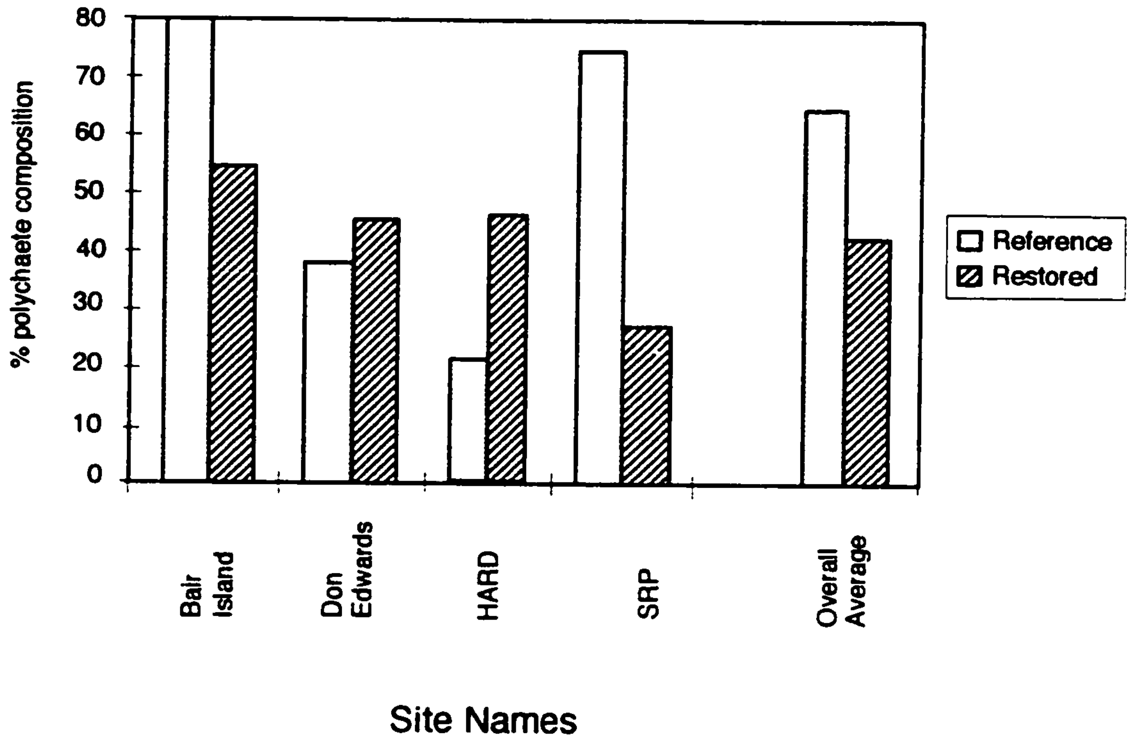

Figure 16. Percent Oligochaete composition by sites. Overall averages are calculated with out the HARD sites.

Table 4

Species Evenness, Diversity and Richness: Sites Ranked from Highest to Lowest.

Site Name	Evenness *(J)* $H/Hmax$	Diversity $H=-\sum p_i ln p_i$	Species Richness
BI rest	0.100	1.666	8
BI reference	0.095	1.589	8
DE reference	0.091	1.507	7
HARD rest	0.076	1.261	7
SRP reference	0.067	1.115	7
DE rest	0.058	0.968	7
HARD reference	0.055	0.919	8
SRP rest	0.050	0.828	7

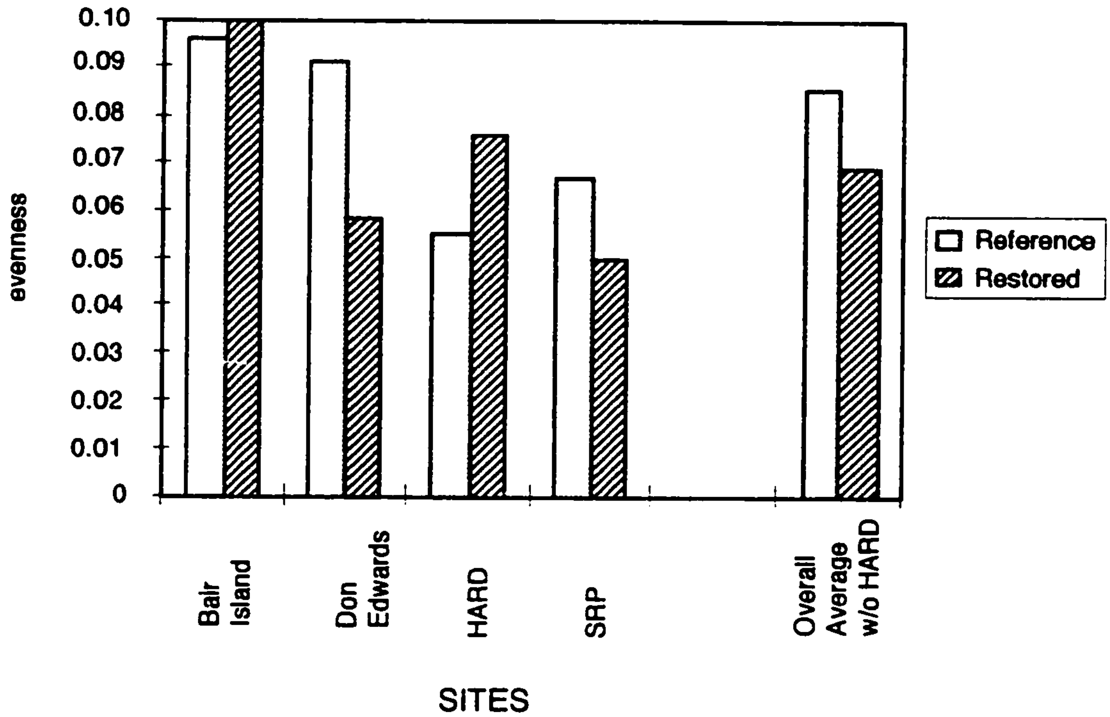

Figure 17. Species evenness by site. Overall average is calculated without HARD sites.

Table 5

Macro-scale Pearson Moment Correlation Results

	Oligo	Evenness	Abund	PC_oligo	PC_poly	Vol. Org.
Oligo	1.000					
Evenness	-0.727	1.000				
Abund	0.590	-0.141	1.000			
PC_oligo	0.886	-0.792	0.172	1.000		
PC_poly	-0.778	0.552	-0.233	-0.896	1.000	
Vol. Org.	-0.696	0.819	-0.362	-0.618	0.508	1.000

Legend: Oligo, oligochaete abundance; Evenness, a diversity index; Abund, total invertebrate abundance; PC_oligo, percent oligochaete abundance; PC_poly, percent polychaete Abundance; Vol. Org., volume organic matter.

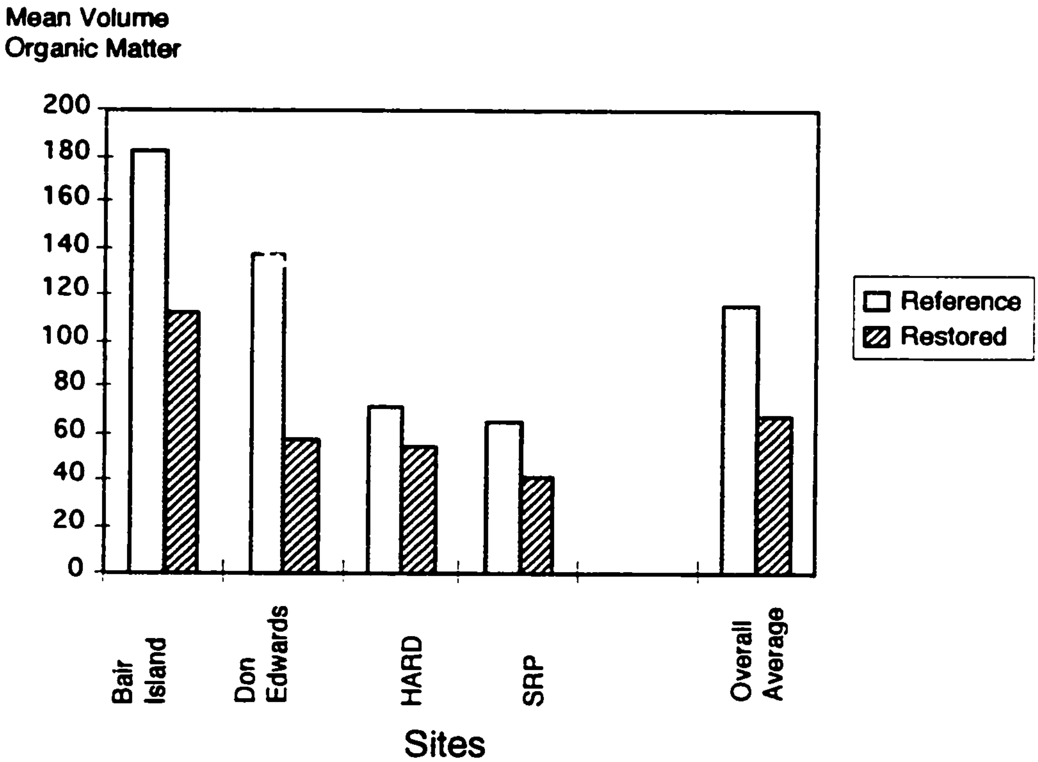

Figure 18. Volume of organic matter by sites.

DISCUSSION

PCA and Canonical Correlation Discussion

Reference sites were found to have high factor 2 scores and were significantly different from restored sites in the PCA ordination. High factor 2 scores represented sites that contained high salinity, low percent cordgrass cover, high pickleweed cover, neutral pH, high volume of organic matter, low temperatures and low dissolved oxygen. This result suggests that high organic matter, high percent plant cover, and lower temperatures, or a more direct proximity to the tidal water, may be appropriate goals to strive for in SF bay restoration efforts, although no one measure can account for all the needs of all marsh fauna. The canonical correlations demonstrate the different requirements of marsh species. Some species, such as one oligochaete species, preferred low percent vegetation, redox and volume organic matter, while other species, such as polychaete A, preferred habitats that were completely opposite.

Canonical correlations showed that a high abundance of oligochaetes and low abundance of nematodes and polychaete A were correlated with low redox, low salt concentration, basic pH, low temperature, low volume organic matter, and low percent plant cover. This type of habitat and invertebrates was predominately represented by restored sites in MDS and PCA ordinations. High polychaete A, and nematodes were correlated to high redox, high salt, neutral pH, high temp, high volume organic matter, and high percent plant cover. This type of marsh habitat was best represented by the more mature Bair Island sites in MDS and PCA ordinations (see the following sections). This analysis also suggests that some species do have preferences in salinity and temperature ranges.

In the second canonical root, *Macoma, Neanthes* and *Heteromastus* prefer low redox and plant cover. High abundances of the above mentioned species were predominately seen in relatively mature marshes such as DE reference and HARD restored sites. Bair Island sites also possessed a high abundance of these species, suggesting that mature marshes do have a varied habitat that can support a high diversity of species. Other sites were in-between ordination factors and their relationships were not as clear.

MDS Discussion

Most restored sites did not completely emulate their reference site with respect to the channel habitat's infaunal composition. The exception was Bair Island, the restored site was very similar to the reference site. Both of the Bair Island sites contain a high species diversity, richness and evenness. These sites had low percent oligochaete composition and relatively high polychaete populations. Bair Island sites also cluster together in habitat characteristics. They contain a high amount of soil organic matter, high percent plant cover, and high redox depth. Most restored sites had less species evenness, lower amounts of organic matter and were dominance of oligochaetes. This relative maturity of the Bair Island restored site may have been due to its large size, its direct proximity to the Bay, or because this site still retained a complex network of tidal channels even though it had been under salt production. Other researchers have contributed greater marsh maturity to parameters such as larger size and to a greater network of tidal channels or edge effects (Cammen 1976; Minello, Zimmerman, and Medina 1994; Levin, Talley, and Hewitt 1998)

HARD sites are dissimilar in both invertebrate and habitat characteristics from each other. The restored site tends to have a higher similarity to the Bair Island sites and DE natural site in invertebrate composition. This site also has good species diversity and evenness. Like the Bair Island restored site, the HARD restored site was also fairly large in size, had a good network of tidal channels, and is directly adjacent to the Bay, which may be the reason this site looks relatively mature. The PCA ordination also suggested that the habitat characteristics at the restored HARD site are more like a reference marsh than a restored one. These results also show that site ages are important. In this case, the restored site was older than the reference site. The restoration site had historically been a salt marsh before restoration, whereas the reference site is a very new developing marsh.

The HARD reference site, on the other hand, has one of the lowest species evenness and is dominated by oligochaetes. This site is very similar to SRP and DE restored sites in species composition. HARD reference site habitat characteristics are more similar to restored sites such as the SRP restored site.

Shoreline sites had very similar habitats to each other, but the restored site had not yet developed the species evenness of its reference site. Shoreline restoration site and Don Edwards restoration sites were the most similar, and clustered together in both habitat and invertebrates ordinations. The HARD reference site, SRP restored, and DE restored sites all were relatively small sites with a poor network of tidal channels. These conditions may contribute to the slower development of these sites, or it could be that these marshes are examples of 10-15 year old marshes in the south Bay channel habitats.

Don Edwards sites were very different from each other. The natural site stood alone in both habitat and invertebrates, although it did resemble the BI sites in one dimension in each ordination. It was closest to HARD restored in invertebrate attributes and in many habitat attributes. It was next similar to the Bair Island sites in both habitat and environmental attributes. The restored site on the other hand, was more similar to 10 to 15 year old marshes such as the SRP sites and the HARD reference site. The DE restored site has not yet developed habitat or invertebrate assemblages at the level of its reference site.

Even though the restored sites tend to be similar in ages, they are very different in maturity. BI restored site very closely resembles its reference site. It has a high polychaete population and low oligochaete population, and relatively high amounts of soil organic matter. Marshes that are close to 10 years of age tend to be very similar in species development. They are dominated by oligochaetes. Habitats between sites can vary, and this variation argues for the need of having references site as close as possible geographically to a restored site.

Abundance and Diversity Discussion

This study found at least 29 taxa represented in south San Francisco Bay tidal channels. This number is comparable to other tidal marsh studies. Netto and Lana (1997) observed 36 taxa in the unvegetated lower marsh areas in Brazil. Thirty eight taxa were reported by Sardá, Foreman, and Valiela (1995) in an east coast marsh, and Levin, Talley and Hewitt (1998) found between 22- 32 species per marsh in southern California. Overall, estuaries are known for their low species diversity. It is not known how the large number of non-native invertebrates species in Bay affects diversity, but it is generally believed that non-natives will often decrease diversity of an ecosystem.

Natural sites appeared to have a higher percent composition of polychaetes (38 - 80%) than oligochaetes (14 - 49%). The percent oligochaetes to percent polychaete composition were negatively correlated to each other ($r = -.90$). Levin, Talley and Hewitt (1998) found oligochaetes made up 35 to 89% of the macrofauna in southern California salt marshes, and polychaetes formed 10-22%. *Capitella* spp., *Polydora cornuta* and *Streblospio benedicti* were the dominate polychaetes found in their study. This study found a higher abundance of polychaetes primarily due to the presence of polychaete A. Minello and Zimmerman (1992) also found polychaete densities higher at natural sites.

Restored sites in this study appeared to have higher percent composition of oligochaetes (50 - 75%) than polychaetes (21 - 46%). BI restored site had 12% oligochaetes and 55% polychaetes, which tended to be more in the range of natural sites than restored sites. Levin, Talley and Hewitt (1998) considered oligochaetes to be a sign of a mature marsh since they did not colonize until after 4 years. In this study, oligochaetes were found to be significantly higher in 10 to 20 year old restored marshes, with some restored sites containing as much as 75% oligochaetes, while high polychaete composition was indicative of very old marshes.

Levin, Talley and Hewitt (1998) determined oligochaetes to be the key taxa that differentiated sites. Little is known about the function of oligochaetes in salt marshes, but their large numbers suggest that research is needed on oligochaete ecology to improve our understanding of marsh function.

This study found polychaetes also were good indicators of young versus old marshes. Natural sites tended to have a higher percent *Streblospio benedicti* (20%) than restored (4%). Levin, Talley and Hewitt (1998) found that southern California marshes had an overall abundance of 38% *Streblospio benedicti*, and 48% oligochaetes. Although *S. benedicti* is considered an opportunistic species, it maintains high populations in older marshes.

Diversity was found to be negatively correlated to oligochaete abundance in this study, suggesting a more transitory role for this taxa. Volume of organic matter was positively correlated to diversity, whereas oligochaete abundance was negatively correlated to volume debris. This suggests that organic matter, and diversity and percent polychaete and oligochaete composition, may be useful predictors in marsh maturity.

Species evenness was found to be the greatest in both BI sites and the DE reference site (between 0.1-0.091). This may be mostly attributed to the higher amount of organic matter at these sites. Other studies have attributed greater diversity to factors such as the size of the site and edge effects of tidal channels (Cammen 1976; Minello, Foreman, and Medina 1994). The BI sites and the DE reference site were the largest sites in this study and appeared to have well formed tidal channels. Although SRP reference site is also fairly large, being comparable to the DE reference site in size, the SRP sites were found to contain the lowest species diversity of the paired sites. These sites have lower salinity and organic enrichment which affect their diversity. SRP sites are located close to Coyote Creek, Guadalupe River, and San Francisquito Creek, which is the sewage outfall for the City of San Jose. Nutrient-rich fresh water flowing into the southern portion of the Bay could affect this site. Nutrient enrichment is known to lead to reduced infauna complexity and shorter food webs that are dominated by deposit feeders, but few filter feeders (Pearson and Rosenberg 1978). This could be the case for the SRP sites. Their infaunal communities tend to be less diverse and are dominated by deposit feeders, especially oligochaetes, and contain relatively few bivalves or filter feeders. Oligochaetes are often found in areas of high nutrient enrichment and pollution.

This study found few of the known first order opportunistic species, such as *Capitella* spp. or *Polydora* spp., in any of the marshes. This suggests that these marshes are beyond the colonizing stages, but rather are in a secondary or intermediate successional phases. Abundance was found to be higher at restored sites which also suggests an intermediate successional stage (Pearson and Rosenberg 1978). High abundance and large differences of populations in *S. benedicti* (32%) at the HARD restored site, and nematodes in the BI restored site (32%), could also be viewed as transitional population fluxes.

RECOMMENDATIONS

Several physical factors that appeared to greatly affect species composition were volume of organic matter, vegetation, and redox. Volume organic matter is higher in reference marshes and was positively correlated to species diversity and evenness, demonstrating its importance to marsh function. Paying attention to this requirement may enhance marsh diversity and evenness. Each species has a particular environment that it prefers: *Macoma* prefers low redox and low volume organic matter, polychaete A prefers high redox, high percent plant cover and a high volume of organic matter. Vegetation supports a different species composition than mud habitats and plays a role in infauna distribution (Netto and Lana, 1997; this study). Paying attention to habitat parameters such as redox, particle size, and organic matter (for food or refugia) should enhance macrofauna success (Levin, Talley and Hewitt 1998; this study). Having a mosaic of different habitats to allow for functional support of different species is recommended to enhance diversity.

Another possible parameter of success is to measure the amount of soil organic matter. The volume of organic matter was consistently higher in reference marshes than in the corresponding restored marshes. Most of the restored sites, except Bair Island, contained less than 60 mls of organic matter per core sample. Reference marshes contained almost twice as much organic matter, averaging 115 mls per core. To determine a target measure of organic matter for a particular site, a measurement should be obtained from a nearby undisturbed marsh if possible. SRP sites had the lowest volume of organic matter, and BI sites had the highest. It would be unrealistic to attempt to get the SRP restored site volume organic matter to duplicate the BI reference site.

Monitoring diversity and evenness may be a good measure of success. BI sites and DE natural had good species evenness, even though DE had low abundance. Older sites contained species evenness values between 0.067 and 0.095. Ten to fifteen year old marshes contained a very narrow range of evenness values that were between 0.050 and 0.058. Still the most appropriate goals for a particular site should be based on parameters measured from undisturbed marshes that are in close proximity to the restored marsh.

An important recommendation is that a reference site must be geographically close. As seen in this study, the Shoreline sites may never reach the level of diversity, or amount of soil organic matter, of the Bair Island sites due to the different physical conditions in the south Bay. Shoreline sites have lower salinity, and possibly higher nutrient levels, factors that are known to limit polychaete density.

Monitoring may be required for as long as 15 to 20 years. One possible measure that marshes are maturing is the percent oligochaete and polychaete composition. In most restored sites oligochaete composition exceeded 50%, whereas reference marshes had less than 50%. Polychaete composition often exceeded 40% in reference marshes, but were less than 40% in restored marshes. Monitoring oligochaete and polychaete composition until oligochaetes drop below 50%, and polychaetes exceed 40% may be a useful indicator of marsh maturity. This composition may be a good indicator of restoration success and easier to do than a diversity index. However, a diversity index appears to be a better indication of success. The diversity index showed that the DE restoration site is still developing, even though it meets the percent oligochaete and polychaete composition goals set in this section.

More research, that spans several years, is needed in order to reliably set the ecological targets defined in this study. This study is a good starting point for identifying which targets may be important to define marsh maturity. More research is needed on oligochaete ecology to understand their role in marsh function. Oligochaetes were the most abundant macroinvertebrate found in this study but very little literature could be found on this organism. The role of organic matter and its relationship to diversity should be investigated further. Organic matter is known to be a factor in determining marsh maturity, but little is known on its full role in marsh functioning. More studies are also needed on the habitat preferences of infauna to determine appropriate goals for restoration efforts. Infauna preferences to soils and edge effects on inbenthics are other important areas of study. More research is also needed on the effects of organic enrichment and the effect of site size on the inbenthics.

This study confirmed other research on how it clearly takes time for full recovery of marsh ecosystems (Nordby and Zedler, 1991). Twenty years is not enough time to bring a marsh up to full function, however, monitoring for 20 years may be enough time to show that a restoration is progressing toward full recovery.

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APPENDIX A

Sites

	BI ref.	BI restored	DE ref.	DE restored	HARD ref.	BI restored	SRP ref.	SRP restored	Total
Oligo 1	78	87	165.5	444	509	466	89	412	2250.5
Polychaete A	236	249	17.5	335	65	0	206	137	1245.5
S. benedicti	144	46	68	30	52.25	296	47	15	698.25
Oligo 2	26	104	61	60	110	191	24	24	600
Nematode	20	231	9	5	23.25	3	1	8	300.25
H. filiformis	50	54	15.25	1	15	69.5	3	1	208.75
N. succinea	18	26	29	6	8.25	26.5	12.25	4	130
M. baltica	17	16	35.5	15	2.5	32.5	0.75	5.5	124.75
E. lighti	8	25	0	0	0.75	33	0	0	66.75
Polydora spp.	33	0	2	2	4.5	0	4	5	50.5
G. gemma	0	2	7	28	2	5	0	0	44
Cirratulid	4	6	0	7	0	0	1	0	18
Total	634	846	409.75	933	792.5	1122.5	388	611.5	5737.25
Spp.Richness	11	11	10	11	11	9	10	9	

Appendix A continued

	Other species
Insects	Diptera larvae-2 spp.
	Pseudoscorpion
Crustaceans	Corophium
	Orchestia
	Other gammerid
	Ostracod
	Cumacea
Bivalves	*Mya* spp.
	I. demissum.
Gastropods	3 unid. spp.
Isopod	1 unid spp.
Polychaete	1 unid. spp.